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# A Detailed Database of the Chemical Properties and Methane Potential of Biomasses Covering a Large Range of Common Agricultural Biogas Plant Feedstocks

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**Abstract:** Agricultural biogas plants are increasingly being used in Europe as an alternative source of energy. To optimize the sizing and operation of existing or future biogas plants, a better knowledge of different feedstocks is needed. Our aim is to characterize 132 common agricultural feedstocks in terms of their chemical composition (proteins, fibers, elemental analysis, etc.) and biochemical methane potential shared in five families: agro-industrial products, silage and energy crops, lignocellulosic biomass, manure, and slurries. Among the families investigated, manures and slurries exhibited the highest ash and protein contents (10.3–13.7% DM). High variabilities in C/N were observed among the various families (19.5% DM for slurries and 131.7% DM for lignocellulosic biomass). Methane potentials have been reported to range from 63 Nm$^3$ CH$_4$/t VS (green waste) to 551 Nm3 CH$_4$/t VS (duck slurry), with a mean value of 284 Nm$^3$ CH$_4$/t VS. In terms of biodegradability, lower values of 52% and 57% were reported for lignocelluloses biomasses and manures, respectively, due to their high fiber content, especially lignin. By contrast, animal slurries, silage, and energy crops exhibited a higher biodegradability of 70%. This database will be useful for project owners during the pre-study phases and during the operation of future agricultural biogas plants.

**Keywords:** anaerobic digestion; agricultural inputs; biochemical methane potential; biodegradability; lignocellulosic biomasses; manures

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## 1. Introduction

Biogas production has increased in the European Union, encouraged by the European "Green Deal" and the renewable energy policies [1,2]. Between 2000 and 2017, global biogas production quadrupled, from 78 to 364 TW h, which corresponds to a global yearly volume of 61 billion m$^3$ biogas; it is shared mainly among Europe (54%), Asia (31%), and the Americas (14%) [1]. Anaerobic digestion (AD) unit numbers are increasing in Europe, supported by the need to improve green energy supplies. Among the typologies of biogas plants, agricultural biogas plants are gaining increasing interest as a valuable technology to treat agricultural residues and co-products, thereby generating energy and fertilizers and improving farmers' incomes. In 2021, France had approximately 401 AD on farms and 285 centralized or territorial AD (Source: SINOE). In parallel, in 2018, 1555 and 9500 biogas plants were reported in Italy and Germany, respectively [1]. Nonetheless, it appears that the biogas sector is facing a shift in its development paradigm [1]. At the European level, the biogas sector is still dominated mainly by a model based on energy crops, high feed-in tariffs, and local electrical production via combined heat and power units. However, the biogas sector is now moving towards a different model, where organic wastes, agricultural by-products, as well as sequential crops are used mainly as feedstocks, and biogas is upgraded to biomethane for various applications (transportation, chemical production, heat, etc.) [1].

As the number of biogas plants has increased, securing deposits and the need for alternative feedstocks are growing. The main families of inputs for agricultural biogas plants are animal wastes (manures and slurries), lignocellulosic biomasses, energy and sequential crops and silages, and agricultural co-products. To help industrial and biogas operators, a better knowledge of the main chemical properties (organic matter, fibers, proteins, elemental analysis, C/N, COD, etc.) along with biochemical methane potential tests are needed. The C/N ratio of feedstock is another important parameter, and for a good anaerobic digestion process, the C/N ratio must be between 20 and 30 [3,4]. Indeed, if a biogas reactor has a low C/N ratio, there is potential inhibition from ammonia [3,5]. Among the chemical parameters, the content of fibers (cellulose, hemicelluloses, and lignin) and proteins is another important issue that can affect the final biodegradability of substrates [6]. Finally, the information of the elemental analysis (C, H, N, S, and O) is of prime importance, as it will allow determination of both the theoretical chemical oxygen demand (COD) and the theoretical methane potential according to the Buswell equation [7].

Aside from chemical properties, the determination of the methane potential through BMP (biochemical methane potential) tests is important. BMPs allow laboratory-scale measurement of the maximum production of methane generated by the digestion of a single substrate, and in recent decades, several national and international inter-laboratory studies have been carried out to optimize the protocol and define good practices [8–10]. BMP tests are a popular technique to determine the methane potential and biodegradability of organic substrates [11]. Currently, the BMP test is used for the technical and economic analysis of a project, for the design of agricultural biogas plants, and for evaluation of the process performance [8]. BMP tests can also be useful when the biogas plant unit is operating and new biomasses are to be introduced. Table 1 lists recent studies that provided detailed BMP data of different organic wastes along with the ISR (inoculum-to-substrate ratio) applied. Indeed, the ISR of the BMP is one of the crucial parameters, and the generally recommended values are between 2 and 4 [9,11]. In parallel with classical BMP tests, a theoretical one can also be estimated according to the elemental composition and the Buswell equation [12] or the COD [13], the chemical composition (lipids, carbohydrates, and proteins) [13], or using McCarty's method [14], allowing determination of the biodegradation rate of a selected substrate.

It is of interest to note that a few publications have provided detailed methane potentials per substrate categories, and they generally provide only min., max., and mean values. Among these publications, Allen et al. (2016) reported methane potentials for 83 organic substrates covering different categories from first-, second-, and third-generation biomasses with agricultural wastes, agro-industrial wastes, food residues, and seaweeds [5]. In parallel, Garcia et al. (2019) reported a detailed methane potential database of more than 50 agricultural and food processing substrates [15]. Similarly, Godin et al. (2015) referenced the methane potential of 569 plant biomasses [16]. In parallel, other studies reported exhaustive lists of the methane potentials of 56 agricultural wastes [17], 48 maize sample silages [18], 43 crop species [19], 12 lignocellulosic biomasses [6], and 30 organic wastes [14].

To date, there is clearly a lack of information in the literature regarding data about the chemical and methane potentials of a large spectrum of agricultural biogas plant feedstocks. This publication aims to highlight the characterization of 132 substrates shared by five different families: cereal and residue (CER), energy crop and silage (ENSI), lignocellulosic matter (LCM), manure (MAN), and slurry (SLU). The selection of substrates was based on their frequency of inclusion in agricultural biogas plants. First, various chemical properties (organic matter, fibers, proteins, elemental analysis, C/N, COD, etc.) were analyzed for the 131 substrates. Then, methane potentials were assessed on these substrates and biodegradability rates (defined as the ratio of the BMP assay yield to the theoretical Buswell yield) were calculated.

**Table 1.** Literature data on large sets of BMP references for organic substrates. N.: number of samples, ISR: inoculum–substrate ratio, MSW: municipal solid wastes, and WWTP: wastewater treatment plant. Description of the samples can be found in the Appendix B.

| Reference | Data Access | Sample Description | N. (Total Number) | ISR | Min BMP | Mean BMP ($Nm^3$ $CH_4$/t VS) | Max BMP |
|---|---|---|---|---|---|---|---|
| [14] | Yes | 30 organic substrates, including 2 raw manures, 9 food residues, 5 invasive aquatic plants, and 6 other organic wastes | 22 | 1 | 122 | 341 | 649 |
| [20] | Yes | Reed canary grasses | 14 | 0.8 | 283 | 348 | 417 |
| [21] | Yes | 11 crops | 41 | 2 | 177 | 311 | 401 |
| [22] | Yes | 4 grasses and 2 legume species | 61 | 2 | 265 | 338 | 422 |
| [5] | Yes | Biomasses from first-, second-, and third-generation: 6 cereal crops, 3 oilseed rapes, 7 root crops, 5 grass silages, 2 baled silages, 8 other grass substrates, 7 dairy slurries, 4 other agricultural wastes, 4 milk processing wastes, 4 abattoir wastes, 7 miscellaneous wastes, 10 domestic and commercial food wastes, 3 alternative waste substrates, and 12 seaweeds | 83 | 2 | 99 | 328 | 805 |
| [23] | Yes | 20 sludge samples | 20 | 2–2.5 | 58 | 181 | 318 |
| [17] | Yes 51/57 | 18 plants, 12 grasses, 5 bushes, 16 trees, 4 cereals, and 1 straw | 57 | 3 | 104 | 219 | 479 |
| [15] | Yes | 5 energy crops, 8 lignocellulosic biomasses, 7 herbaceous and vegetable by-products, 7 fruit by-products, 6 livestock effluents, and 18 food by-products | 50 | 2 | 71 | 325 | 729 |
| This study | Yes | 46 energy crops and silages, 5 slurries, 31 manures, 17 cereal and agro-industrial residues, and 32 lignocellulosic biomasses | 131 | 3 | 63 | 283 | 551 |
| [24] | Yes Appendix * | 3 animal manures, 3 crop straws, 5 food and green wastes, 2 processing organic wastes, 1 energy grass, and 2 lignocellulosic biomasses | 16 | 2 | 49 | 317 | 811 |
| [18] | Yes Appendix * | 48 maize genotypes selected for diverse maturity and biomass production | 204 | - | 295 | 329 | 355 |
| [16] | Yes Appendix * | 17 Miscanthus, 16 switch grasses, 36 spelt straws, 37 fiber sorghums, 369 tall fescues, 21 immature ryes, and 73 fiber corns | 569 (588) | 2 | 147 | 389 | 589 |
| [19] | Yes Appendix * | 405 silages from 43 crop species | 43 | 2 | 143 | 304 | 425 |
| [25] | No | 68 municipal solid wastes, 7 MSW mix, 9 raw substrates, and 18 lignocellulosic wastes | 20 (102) | 0.5 | 87 | 257 | 226 |
| [26] | No | 95 meadow grasses | 95 | - | 51 | 288 | 406 |

**Table 1.** *Cont.*

| Reference | Data Access | Sample Description | N. (Total Number) | ISR | Min BMP | Mean BMP (Nm$^3$ CH$_4$/t VS) | Max BMP |
|---|---|---|---|---|---|---|---|
| [27] | No | 57 agro-industrial biomasses, 1 macroalgae, 20 biowastes, 4 energy crops, 11 fatty wastes, 14 meat wastes, 2 co-digestion mixtures, 66 WWTP, 42 plants and vegetables, 18 agro-industrial sludges, 30 sewage sludge WWTP, and 31 municipal solid wastes | 296 | 2–5 | 0 | 291 | 1344 |
| [28] | No | 33 energy crops, 15 lawn grasses, 19 hedge trimmings, and 21 wild plants | 88 | 3 | 104 | 251 | 502 |
| [29] | No | 23 anaerobic sludges, 30 standard compounds, 50 household wastes, 10 agriculture wastes, 19 sewage sludges, and 6 lipid-rich wastes | 138 | 2 | 39 | 361 | 943 |
| [30] | No | 48% agricultural residues, 29% animal beading wastes, 6% AD feedstock, AD digestates, lipid wastes, algae, MSW, and agro-industrial wastes | 289 | 2.8 | 56 | 287 | 879 |
| [6] | No | 12 lignocellulosic biomasses | 12 | 2 | 155 | 225 | 300 |

* data are not provided directly in the publication but in an appendix of the authors publications.

## 2. Materials and Methods

### 2.1. Sampling

Feedstocks were collected in thirty agricultural biogas plant units operating with agricultural feedstocks on the national level. Of these, 75% were operating in wet AD and 25% in dry AD. These 132 inputs are regrouped into five main families: cereal and agro-industrial co-products (CER), energy crop and silage (ENSI), lignocellulosic matter (LCM), manure (MAN), and slurry (SLU). A description of the dataset is available in the Appendix A (Tables A1 and A2).

### 2.2. Elemental Composition and Fiber Analysis

The elemental composition of each feedstock was assessed by an elemental apparatus (varioMicro V4.0.2, Elementar®, Langenselbold, Germany), after being dried at 60 °C until constant weight and ground into 1 mm particles using a centrifuge mill (SR 200, Retsch, Haan, Germany). Each COD was then calculated on the basis of this analysis using Equation (1) [31]:

$$COD\left(\frac{gCOD}{gCxHyOz}\right) = 8 \times \frac{4x + y - 2z}{12x + 4 + 16z} \quad (1)$$

The protein content was estimated on the basis of the nitrogen elemental composition multiplied by 6.25 [32].

For fiber analysis (e.g., cellulose, hemicelluloses, and lignin-like), 80 mg of sample was hydrolyzed with 0.85 mL of $H_2SO_4$ acid (72%) for 1 h at 30 °C in continuously shaken tubes for thorough mixing (450 rpm) using closed vessels to prevent evaporation. Then, 23.8 mL of deionized water was added, and the vessels were heated to 121 °C for one hour under magnetic agitation (450 rpm). After cooling, the insoluble residue was separated by filtration through 1 µm glass fiber paper (GFF, WHATMAN®, Maldstone, UK) into a soluble phase (structural carbohydrates) and a solid phase (lignin and ash). The filtrate was further filtered using nylon filters (0.2 µm) and analyzed for glucose, xylose, and arabinose by high-performance liquid chromatography (1260 infinity II technology, Agilent, Santa Clara, CA, USA) equipped with a Hi.Plex H coupled to a UV detector. The crucible and the fiberglass paper were dried at 105 °C for 24 h to determine the content of Klason lignin-like material by weighing. The cellulose-like and hemicelluloses-like contents were determined using the following equations:

$$\text{Cellulose} - \text{like}\ (\%\ \text{DM}) = \frac{\text{Glucose}\ (\%\ \text{DM})}{1.11} \tag{2}$$

$$\text{Hemicelluloses} - \text{like}\ (\%\ \text{DM}) = \frac{\text{Xylose}\ (\%\ \text{DM}) + \ \text{Arabinose}\ (\%\ \text{DM})}{1.13} \tag{3}$$

where 1.11 is the conversion factor of polymers based on glucose-to-glucose monomers, and 1.13 is the factor for converting polymers based on xylose (arabinose and xylose) into monomers [33].

### 2.3. Biochemical Methane Potential Measurement (BMPexp)

The procedure for BMP tests has been well-documented in a previous study [30] and followed the inter-laboratory study recommendations [8,34]. Feedstocks were stored at 5 °C if the storage period was less than or equal to three days or at −20 °C if the storage period exceeded three days and thawed at 6 °C before testing. Used inoculum was agitated, maintained at 38 ± 1 °C, and fed regularly with green grass and wastewater sludge at the laboratory of APESA facility. Regular checks were performed by measuring the pH, dry matter, and volatile solids. DM and vs. were obtained by loss on ignition (same as for feedstocks), and the pH was assessed using a 340i pH meter fitted with Sentix® electrodes (WTW, Weilheim, Germany). The main properties of the inoculum were TS (% fresh mass): 3.8 ± 0.3%; vs. (% TS): 64.4 ± 1.5%; pH: 8.3 ± 0.2; volatile fatty acids (VFAs): 300 mg eq. acetate $L^{-1}$; and ammonium content: 2.1 g $N\text{-}NH_4^+\ L^{-1}$. The inocula complied with the quality criteria proposed by [10].

The BMP tests were carried out under mesophilic conditions in duplicate, and 500 mL reactors were filled with 300 mL of an inoculum/substrate ratio of 3 g VS/g VS. After filling, each bottle was flushed with $N_2$ gas for 30 s, incubated at 39 °C, and degassed after 1 h. Each day, manual homogenization was performed, and biogas production followed using an electronic manometer device (Digitron 2023P, Digital Instrumentation Ltd., London, UK) and expressed in normal liters (at 0 °C, 1.013 hPa). Once a week, the gas composition was analyzed by gas chromatography (Varian GC-CP4900, Agilent, Santa Clara, CA, USA) equipped with two columns. For $O_2$, $N_2$, and $CH_4$, a Molsieve 5A PLOT column at 110 °C was used, and for $CO_2$ analysis, a HayeSep A set at 70 °C was used. The injector and detector temperatures were set at 110 °C and 55 °C, respectively. Two standard gases for calibration were used: one composed of 9.5% $CO_2$, 0.5% $O_2$, 81% $N_2$, and 10% $CH_4$, and the other composed of 35% $CO_2$, 5% $O_2$, 20% $N_2$, and 40% $CH_4$ (special gas from Air Liquide®, Paris, France). The BMP tests concluded when the biogas production reached a stationary state and did not vary for more than 0.5% during three consecutive days. Blank (inoculum only) and positive controls (cellulose, Tembec®, Montréal, QC, Canada) were run in parallel in duplicate.

The theoretical BMP was calculated on the basis of the elemental characterization (CxHyOzNnSs) using Equation (4) (Achinas and Euverink, 2016):

$$BMPth\ (LCH_4/kg\ VS) = \frac{22.4 \times \left(\frac{x}{2} + \frac{y}{8} - \frac{z}{4} - \frac{3n}{8} - \frac{s}{4}\right)}{12x + y + 16z + 14n + 32s} \tag{4}$$

where 22.4 is the molar volume of an ideal gas.

Finally, the percentage of biodegradation is the ratio between the experimental BMP and the theoretical BMP.

$$Biodegradation\ (\%) = \frac{BMPexp}{BMPth} \tag{5}$$

## 3. Results

### 3.1. Chemical Composition of the Various Biomasses

The feedstock compositions are described in Figure 1 (overall and for each family, more data are available in SD Table 1). Among the five families, the distribution was as follows: 47% energy crops and silages, 32% lignocellulosic biomasses, 31% manures, 17% cereal co-products and residues, and 5% slurries. The minimum, maximum, and average values of the different chemical properties (DM, VS, C/N, fibers, proteins, and COD) are shown for all the families in Tables A1 and A2. In order to have a better sense of the inter-family variability, the most important parameters (i.e., VS/DM, COD, C/N, and protein content) are presented as boxplots (Figure 1) and the fiber compositions as radar graphs (Figure 2).

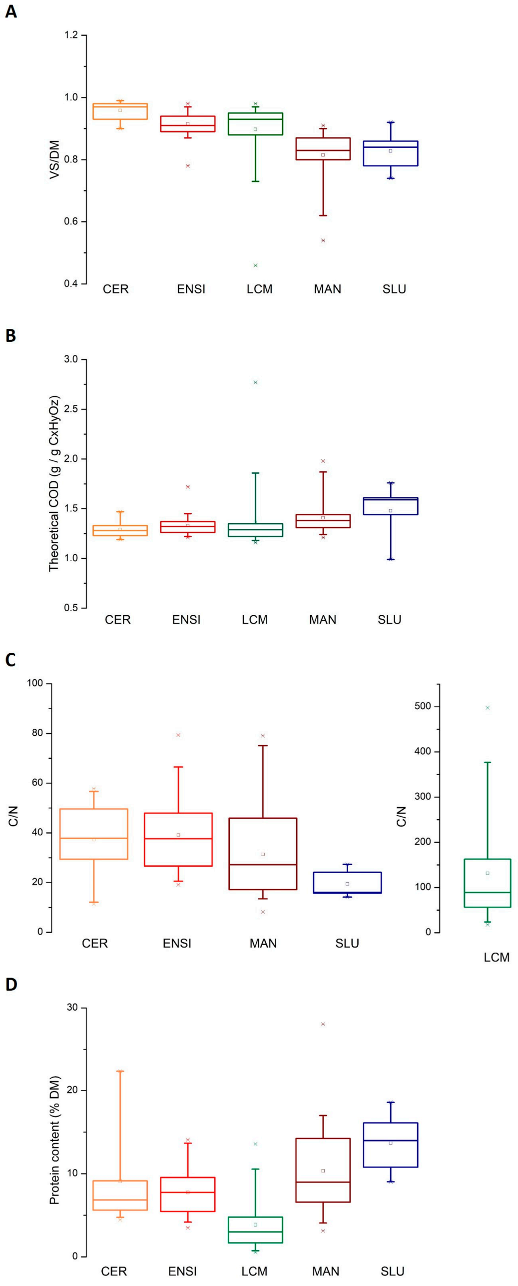

**Figure 1.** (**A**–**D**) Boxplots of chemical composition variabilities: VS/DM, COD, C/N, and protein content. Medians are the horizontal lines and means are represented by squares. Families: cereal and residue (CER), energy crop and silage (ENSI), lignocellulosic matter (LCM), manure (MAN), and slurry (SLU).

First of all, higher ash contents were reported for manures and slurries compared with the other families investigated. In terms of proteins, higher contents were also reported for manures and slurries. Indeed, mean protein contents of 10.4 and 13.7% DM were reported for animal manures and slurries, respectively. By contrast, lignocellulosic biomasses exhibited the lowest protein content, at 3.9% DM. Allen et al. (2016) reported protein contents varying from 12.3% DM to 18.5% DM for different animal slurries [5]. Similarly, Li et al. (2013) estimated protein contents of 13.7% DM, 17.5% DM, and 21% DM for swine, dairy, and chicken manures, respectively. Li et al. (2013), on the other hand, reported lower values ranging from 2.5% DM to 5.6% DM for lignocellulosic biomasses [24]. The chemical oxygen demand is another important parameter in anaerobic digestion monitoring, as it can allow determination of mass balances and the theoretical methane potential [13]. Little variability in the main COD was observed for the five families, with values ranging from 1.3 to 1.5 g/g VS. Scarce information is available in the literature regarding these parameters, as only Labatut et al. (2011) have reported it for a range of 30 substrates (mono- and co-digestion). For manure, they found a COD ranging from 0.7 to 1.3 g/g, with a mean of 1.0, which is considerably lower than our values, and higher values for biowaste substrates, with a mean of 6.4, ranging from 0.9 to 28.8 g/g [14]. The fiber content (i.e., cellulose, hemicelluloses, and lignin) was also reported for the five families, and higher contents were observed for lignocellulosic biomasses and manures, similar to the values previously reported in the literature [6,14,24].

Finally, the C/N ratio was also reported for the five families. The C/N ratio is a very important parameter for the long-term continuous digestibility of a substrate. Ideally, it should be between 25:1 and 30:1 to facilitate optimal growth of micro-organisms [5]. For this parameter, high variabilities were observed with higher values of C/N for lignocellulosic biomasses, with a median of approximately 90 and an average of 132. All the other groups have means or averages between 19 and 40. Yet, the C/N ratio is based on the elemental analysis, requiring dry samples. Volatilization of ammoniacal nitrogen or volatile compounds can differ depending on the substrate. A comparison of these results with C/N ratios in the literature points out that an overestimation occurred for slurry and manure families [15,35,36]; similar results are obtained for CER and LCM [5,15], whereas ENSI family C/N ratios are underestimated [5,15,37,38]. Extrapolations cannot be readily performed, as they can depend on the feedstock composition, type, harvest, storage, etc. As an example, manure C/N ratio means have been found to be approximately 16 for cattle manure, 9 for poultry manure, and they are higher for horse manure (between 15 to 150, depending on the type and proportion of litter) [35,36,39].

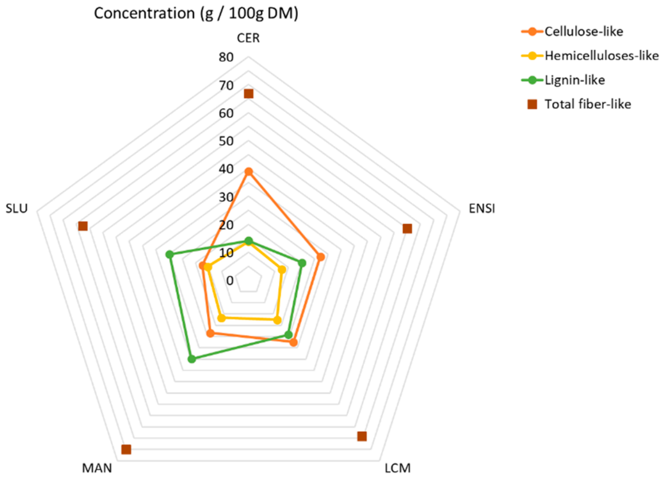

**Figure 2.** Means of the different family composition of fibers. Families: cereal and residue (CER), energy crop and silage (ENSI), lignocellulosic matter (LCM), manure (MAN), and slurry (SLU).

### 3.2. Biochemical Methane Potential of Feedstock

Another important parameter in the monitoring and optimization of agricultural biogas plants is the value of the methane potential. Methane potentials were assessed in this study by BMP tests performed on the 132 agricultural substrates shared in five families: cereals and agro-industrial co-products, lignocellulosic biomass, energy crops and silages, animal manures, and slurries (Figure 3).

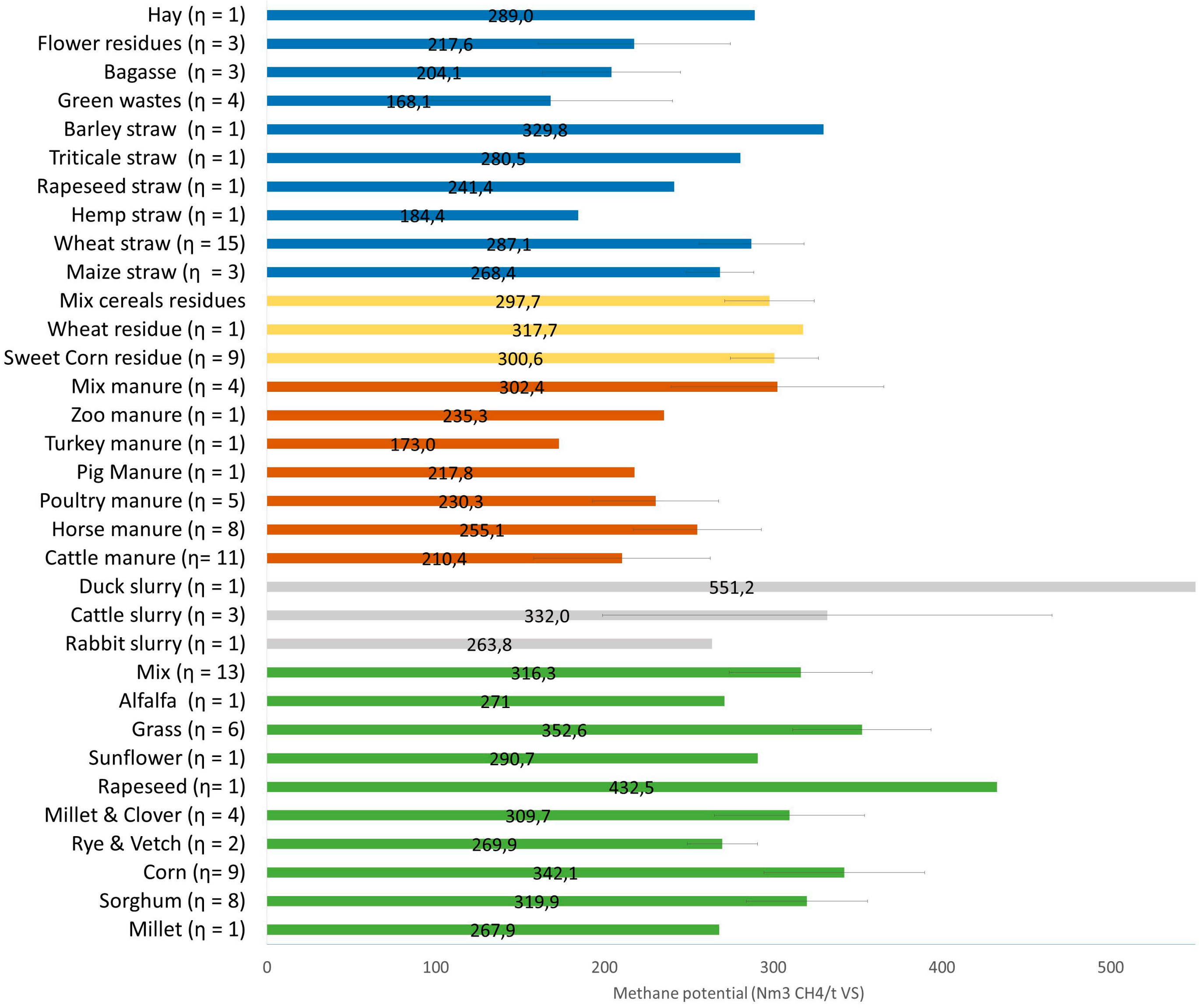

**Figure 3.** Methane potentials of the different categories of the five families. Families: cereal and agro-industrial residue in grey (CER), energy crop and silage in blue (ENSI), lignocellulosic matter in green (LCM), manure in red (MAN), and slurry in yellow (SLU).

As shown in Table 1, a large variability in methane potentials was observed among the different families, with methane potentials ranging from 63 $Nm^3$ $CH_4$/t VS (green waste) to 551 $Nm^3$ $CH_4$/t VS (duck slurry), with a mean value for the 132 organic samples of 284 $Nm^3$ $CH_4$/t VS.

#### 3.2.1. Cereal and Agro-Industrial Residues (CER)

The first family investigated was cereal and agro-industrial residues (*n* = 17). The cereals were obtained from the cereal agro-industry and silos, whereas the maize was from the sweet corn industry. Methane potentials of 298, 301, and 318 Nm$^3$ CH$_4$/t VS were reported for cereal residues, sweet corn residues, and wheat residues, respectively. Garcia et al. (2019) reported a similar methane potential, with values of 345 Nm$^3$ CH$_4$/t VS for a mix of cereals [15]. Luna DeRisco et al. (2011) also investigated the methane potentials of grain mill residues, and methane potentials of 274–386 Nm$^3$ CH$_4$/t VS were reported [40]. In parallel, Garcia et al. (2019) also reported methane potentials ranging from 204 to 345 Nm$^3$ CH$_4$/t VS for ten agro-industrial co-products (from the vegetables and fruits industry) [15].

### 3.2.2. Manures (MAN)

The methane potential of various animal manures was investigated. Manures are organic matter, derived mostly from animal feces and urine but also normally containing plant materials (generally wheat straw) that have been used as bedding for animals. Methane potentials of 173, 210, 217, 230, 235, and 250 Nm$^3$ CH$_4$/t VS were determined for turkey, cattle, pig, poultry, zoo, and horse manures. Such data are in the same range as the values reported in the literature [24,41,42]. Kafle and Chen (2016) investigated the methane potential of five different livestock manures (dairy manure (DM), horse manure (HM), goat manure (GM), chicken manure (CM), and swine manure (SM)). The BMPs of DM, HM, GM, CM, and SM were determined to be 204, 155, 159, 259, and 323 Nm$^3$ CH$_4$/t VS, respectively [41]. Similarly, Cu et al. (2015) also reported methane potentials of various animal manures, and the highest BMP in this study was from piglet manure at 443.6 Nm$^3$ CH$_4$/t VS, followed by cow, sow, chicken, rabbit, buffalo, and sheep manures at 222, 177.7, 173, 172.8, 153, and 150.5 Nm$^3$ CH$_4$/t VS, respectively [42]. Similarly, Garcia et al. (2019) reported methane potentials of 97, 128, 200, and 208 Nm$^3$ CH$_4$/t VS for bovine, pig, rabbit, and poultry manures, respectively [15]. Yang et al., 2021 also reported methane potentials of 160 Nm$^3$ CH$_4$/t VS for dairy manure, 200 Nm$^3$ CH$_4$/t VS for goat manure, and 325 Nm$^3$ CH$_4$/t VS for swine manure [43]. It can be observed that the methane potentials of our studies are in the same range as the literature data, although some differences can be observed for the same manure families, as the methane potential can be influenced by the type of farm, the duration of storage, and the storage method. Finally, Carabeo-Perez et al. (2021) also investigated the methane potential from various herbivorous animal manures. Methane yield potentials of 245, 326, and 112 Nm$^3$ CH$_4$/t VS were obtained for horse, rabbit, and goat manures, respectively, influenced by the difference in their digestive systems to digest the grass feedstock [44]. Finally, Li et al. (2013) determined methane potentials of 51, 295, and 321 Nm$^3$ CH$_4$/t VS for dairy, chicken, and swine manure, respectively [24].

### 3.2.3. Animal Slurries (SLU)

Animal slurries are manure in liquid form, i.e., a mixture of excrements and urine of domestic animals, including water and/or small amounts of litter. Slurry methane potentials were also investigated in this study, with methane potentials ranging from 263 to 551 Nm$^3$ CH$_4$/t VS. As shown in Figure 3, a high variability was observed for cattle slurries, which can be explained by differences in the storage type and duration. In terms of liquid manures, little information is available in the literature [5,14]. Labatut et al. (2011) reported a methane potential of 261 Nm$^3$ CH$_4$/t VS for liquid dairy manure. Allen et al. (2016) investigated the methane potentials of different slurries (dairy, pig, and beef). Methane potentials of 99 and 311 Nm$^3$ CH$_4$/t VS were reported for pig and beef slurries, respectively. In terms of dairy slurries, methane potentials ranging from 136 to 239 have been reported [5]. Garcia et al. (2019) also reported methane potentials of 35 and 137 Nm$^3$ CH$_4$/t VS for bovine and pig slurries, respectively [15].

### 3.2.4. Silages and Energy Crops (ENSI)

Silages and energy crops are another type of substrate generally found in agricultural biogas plants. In our study, of the 46 organic substrates investigated, the methane potentials ranged from 187 Nm$^3$ CH$_4$/t VS to 461 Nm$^3$ CH$_4$/t VS. For instance, average methane potentials of 320, 342, and 352 $Nm^3$ $CH_4$/t VS were reported for sorghum, corn, and grass samples, respectively. The methane potentials of silages and energy crops have been widely investigated in the literature in recent decades, and the values obtained in this study are in the same order [5,15,18,19]. For instance, Garcia et al. (2019) investigated the methane potential of five energy crops and reported methane potentials ranging from 253 $Nm^3$ $CH_4$/t VS (millet, *Panicum milliaceum* L.) to 351 $Nm^3$ $CH_4$/t VS (triticale, *Triticum aestivum* L.). Similarly, Allen et al. (2016) reported the methane potential of 18 energy crops, and the methane potentials ranged from 281 $Nm^3$ $CH_4$/t VS (winter oats) to 398 $Nm^3$ $CH_4$/t VS (turnips). Similarly, Allen et al. (2016) also investigated the methane potentials of different silages and reported methane potentials varying from 311 $Nm^3$ $CH_4$/t VS (Savazi grass silage) to 433 $Nm^3$ $CH_4$/t VS (silage bales). Finally, Hermann et al. also investigated the methane potentials of 43 crops, including main and secondary crops, catch crops, annual grass, and perennial crops [19].

### 3.2.5. Lignocellulosic Biomasses (LCM)

The methane potentials of 33 lignocellulosic biomasses were also investigated. The methane potentials ranged from 63 $Nm^3$ $CH_4$/t VS (green waste) to 330 $Nm^3$ $CH_4$/t VS (barley straw). Lower methane potentials were observed for green waste residues, likely due to their high content in fibers, and especially in lignin, which has been shown to be poorly degraded in the anaerobic digestion process [19,45]. Similar methane potentials on lignocellulosic biomasses have been reported previously in the literature [6,15]. Indeed, Monlau et al. (2012) reported the methane potentials of twelve lignocellulosic biomasses ranging from 155 $Nm^3$ $CH_4$/t VS (sunflower stalks) to 300 $Nm^3$ $CH_4$/t VS (Jerusalem artichoke tubers). Similarly, Garcia et al. (2019) reported methane potentials ranging from 282 $Nm^3$ $CH_4$/t VS (coconut fibers) to 425 $Nm^3$ $CH_4$/t VS (corn, *Zea mays* L.). Similarly, Dinuccio et al. (2010) reported methane potentials ranging from 225 to 424 $Nm^3$ $CH_4$/t VS [46]. Perennial crops exhibited the lowest methane potentials, with values ranging from 203 $Nm^3$ $CH_4$/t VS (cup plant) to 260 $Nm^3$ $CH_4$/t VS (tall wheatgrass). The highest methane potential of the various crops investigated was reported for forage triticale, with a methane potential of 371 $Nm^3$ $CH_4$/t VS.

## *3.3. Practical Implementation of this Database*

To assist the reader and user in exploiting this publication, a summary table is provided in Table 2 with the main physicochemical parameter and methane potential values for the various substrate families investigated in this study. As previously discussed, the methane potentials ranged from 63 $Nm^3$ $CH_4$/t VS (green waste) to 551 $Nm^3$ $CH_4$/t VS (duck slurry), with a mean value for the 132 organic samples of 284 $Nm^3$ $CH_4$/t VS.

To better understand the ability of the various organic wastes that were tested to be degraded in the AD process, a biodegradation yield (based on the ratio of the experimental and theoretical BMP) was calculated using the Buswell formula. The family biodegradation yields are presented in Figure 4.

**Table 2.** Chemical composition of the families (FM: fresh matter; DM: dry matter; and VS: volatile solids). Families: cereals and residues (CER), energy crops and silage (ENSI), lignocellulosic matter (LCM), manures (MAN), and slurries (SLU).

| Family | CER | ENSI | LCM | MAN | SLU |
|---|---|---|---|---|---|
| Sample number | 17 | 46 | 33 | 31 | 5 |
| DM | 21.9–89.4 | 15.5–69.0 | 28.4–90.6 | 8.0–81.6 | 4.7–26.3 |
| (% FM) | 57.2 | 27.3 | 71.2 | 39.2 | 13.2 |
| VS | 21.4–85.4 | 13.5–62.4 | 26.4–86.0 | 5.3–69.1 | 3.5–24.2 |
| (% FM) | 54.3 | 25.0 | 64.3 | 31.8 | 11.4 |
| C | 40.2–44.6 | 38.7–46.7 | 34.5–45.0 | 28.7–43.5 | 35.9–42.1 |
| (% DM) | 42.8 | 42.6 | 42.2 | 38.7 | 39.9 |
| H | 5.8–6.9 | 5.2–6.6 | 4.5–6.3 | 3.8–6.3 | 5.1–6.0 |
| (% DM) | 6.5 | 5.9 | 5.8 | 5.4 | 5.6 |
| N | 0.6–3.8 | 0.5–2.3 | 0.1–2.3 | 0.4–4.6 | 1.6–2.8 |
| (% DM) | 1.4 | 1.2 | 0.6 | 1.6 | 2.2 |
| S | 0.1–0.7 | 0.1–0.9 | 0.1–1.0 | 0.2–1.6 | 0.4–0.7 |
| (% DM) | 0.2 | 0.2 | 0.3 | 0.5 | 0.5 |
| C/N | 11.4–57.8 | 19.1–79.4 | 17.6–497.8 | 8.2–79.1 | 14.2–27.3 |
|  | 37.3 | 39.2 | 131.7 | 31.4 | 19.5 |
| Cellulose-like | 25.8–60.9 | 11.2–52.3 | 15.4–33.6 | 13.6–35.0 | 8.7–26.4 |
| (% VS) | 39.0 | 27.1 | 27.4 | 23.4 | 17.3 |
| Hemicellulose-like | 6.0–21.3 | 6.4–20.5 | 7.8–26.0 | 8.8–21.5 | 7.7–23.5 |
| (% VS) | 13.7 | 12.6 | 17.5 | 15.7 | 15.5 |
| Lignin-like | 5.5–21.4 | 11.4–28.9 | 14.7–50.2 | 20.0–56.5 | 19.1–38.6 |
| (% VS) | 14.1 | 20.3 | 24.2 | 34.9 | 29.8 |
| Proteins | 4.5–22.5 | 3.5–14.1 | 0.6–13.6 | 3.1–28.1 | 9.0–18.6 |
| (% DM) | 9.1 | 7.7 | 3.9 | 10.4 | 13.7 |
| COD | 1.2–1.5 | 1.2–1.7 | 1.2–2.8 | 1.2–2.0 | 1.0–1.8 |
| (g/g (CxHyOz)) | 1.3 | 1.3 | 1.4 | 1.4 | 1.5 |
| Family | CER | ENSI | LCM | MAN | SLU |
| $BMP_{th}$ | 407–469 | 410–582 | 400–920 | 397–659 | 320–568 |
| ($Nm^3$ $CH_4$/t VS) | 434 | 449 | 466 | 466 | 483 |
| BMP | 250–336 | 187–461 | 63–330 | 132–366 | 224–551 |
| ($Nm^3$ $CH_4$/t VS) | 300 | 324 | 251 | 237 | 362 |
| BMP | 56–278 | 41–169 | 23–254 | 13–178 | 10–54 |
| ($Nm^3$ $CH_4$/t FM) | 164 | 78 | 167 | 75 | 35 |

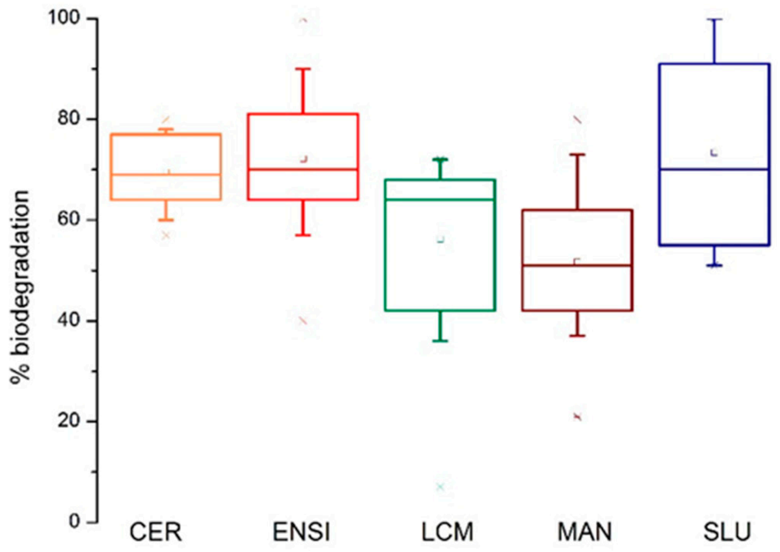

**Figure 4.** Boxplots of biodegradation yields of the five families. Medians are the horizontal lines and means are represented by squares. Families: cereal and residue (CER), energy crops and silage (ENSI), lignocellulosic matter (LCM), manure (MAN), and slurry (SLU).

A majority of families presented a good biodegradation rate, with means between 52 and 73%. Lower degradation rates of only 52 and 56% were reported for manure and lignocellulosic matter, respectively. As manure is a mixture of feces and bedding material, depending on the bedding material used and its concentration, it is not surprising to find similar results between these two families [47]. The biodegradability of organic substrates has been well-documented in the literature for various organic substrates [5,14,15,17,24]. Regarding lignocellulosic biomasses, Triolo et al. (2012) reported biodegradability indices of 32.7%, 39.9%, 44.9%, and 66.6% for wood cuttings, hedge cuttings, wild plants, and lawn cuttings, respectively. Similarly, Li et al. (2013) reported biodegradability indices of 51%, 54%, and 62% for corn stover, wheat straw, and rice straw, respectively. Similarly, Li et al. (2013) reported biodegradation rates of 10%, 63%, and 68% for dairy manure, chicken manure, and swine manure, respectively. Garcia et al. (2019) also reported biodegradability indices varying from 30% to 70% for different animal manures samples. Such lower biodegradation rates for LCM and MAN families can be explained by the higher fiber contents in such biomasses, especially lignin content, which is poorly degraded in the AD process [6,45]. The high nitrogen concentration in animal manures can also be a limiting factor of the expression of the methane potential [42].

In parallel, other families investigated in this study exhibited higher biodegradability rates of 69%, 72%, and 73% for cereal and agro-industrial residues, energy crops and silages, and slurries, respectively. Allen et al. (2016) reported biodegradability indices for sixteen silages from second-generation crops, and three-quarters of the samples exhibited biodegradation rates higher than 75%. Similarly, Garcia et al. (2019) reported biodegradabilities varying from 80% to 100% for various energy crops (i.e., millet, barley, maize, sorghum, and triticale). Garcia et al. (2019) also reported high biodegradabilities of 80% and 90% for flour and cereals. In terms of slurry samples, the results in the literature are more contrasted [5,15]. Indeed, biodegradabilities varying from 20% to 60% have been reported. Such variation can be explained by the difference in the origins of animal slurries as well as the storage duration and typology.

## 4. Discussion

At the end of 2018, annual production of biomethane from AD in the EU corresponded to 2.3 billion m$^3$, with 18,202 biogas plants in operation [1]. Europe is the world leader in biogas electricity production, far ahead of the USA (2.4 GW) and China (0.6 GW) [1]. At the European level, the methanization sector will greatly develop in the years to come with projections up to 64.2 billion m$^3$ in the EU by 2050; this would represent an energetic potential of approximately 640 TW h/year and would require a 30-fold growth of the current biomethane sector [1].

AD will continue to grow in the future, but it is clear that the sector should have better control of not only the management and the use of the deposits but also the identification of new sources of deposit. The BMP test remains an essential tool for characterizing new deposits and determining their pricing.

This publication and the results (Table 1) are intended to contribute to providing data to the scientific community and biogas developers regarding the values of methane potentials and biodegradability indices of different organic substrates and complete previous studies on the subject (Table A3 in Appendix B). In parallel, this study is intended to be a tool for the sizing, optimization, and operation of the biogas sector. All the data obtained for the different feedstocks are available in the Appendix A.

It could be interesting in the future to extend this work and to generate an overall synthesis of all the BMP values listed in the literature by taking into account the studies using a protocol based on the recommendations of interlaboratory guidelines carried out at the international level [10,34]. In parallel, the growing development of the biogas sector requires the mobilization of new resources and organic biomasses, and it will be interesting in the future to focus studies on the evaluation of the methanogenic potential of atypical biomasses (i.e., algae, paper sludges, biodegradable plastics, insect excrements, etc.). An extended open-source BMP database (based on BMP values validated by experts) could be very useful in the future in order to improve the biogas development as well as the monitoring of the energetic performances of biogas plants. Indeed, Holliger et al. (2017) compared methane production from BMPs with biogas production from the same organic materials in full-scale installations [48]. Holliger et al. (2017) highlighted that the measured weekly methane production accounted for 94.0 ± 6.8 and 89.3 ± 5.7% of the calculated weekly methane production for two biogas plants, respectively [48].

Short-term (i.e., 1–2 months), batch-mode anaerobic digestion tests, such as the biochemical methane potential (BMP) assay, are intended primarily to determine methane yields and the biodegradability of substrates [14]. Nonetheless, such testing may fail to truly predict the performance of full-scale anaerobic reactors. For this purpose, semi-continuous laboratory-scale experimental methods are complementary to chemical and BMP analysis. Semi-continuous flow reactors are designed to emulate the conditions of commercial-scale digesters and study their overall performance over time, taking into account co-digestion benefits and potential inhibition.

## 5. Conclusions

In this study, a characterization of 132 common agricultural feedstocks (shared in five families) was carried out in terms of physical properties and methane potentials. Of the various families investigated, manures and slurries exhibited the highest ash and protein contents (10.3–13.7% DM). A high degree of variability in terms of the C/N ratio was observed among the various families, with values ranging from 19.5% DM (slurries) to 131.7% DM (lignocellulosic biomass). In terms of biodegradability, lower values of 52% and 57% were reported for lignocelluloses biomasses, and manures due to their high content in fibers, especially lignin. The AD sector will continue to grow in the future, and such studies can be used as a reference for any operator/manager of units or public authority/financial provider in the future.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Description of the substrates analyzed within the families, where SD is standard deviation, DM is dry matter, FM is fresh matter, VS is volatile solids, BMP exp is the BMP measured, and BMP is the maximum methane potential based on CHNS composition.

| Family | Type | Sub Type | DM | VS | VS/DM | BMP exp | | CV(%) | Biodegradation | C/N | Carbon | | Hydrogen | | Nitrogen | | Sulfur | | Oxygen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | Mean | Mean | Mean | SD | | | | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean |
| | | | (% FM) | | | (Nm$^3$ CH$_4$/t VS) | | | % | | (% DM) | | (% DM) | | (% DM) | | (% DM) | | (% DM) |
| ENSI | Millet | — | 22.9 | 20.8 | 0.91 | 267.9 | 11.9 | 4% | 61 | 54.1 | 42.7 | 0.1 | 5.3 | 0.1 | 0.8 | 0.1 | 0.2 | 0.1 | 41.9 |
| ENSI | Sorghum | — | 18.4 | 16.2 | 0.88 | 361.8 | 4.1 | 1% | 79 | 28.2 | 42.3 | 0.0 | 5.6 | 0.2 | 1.5 | 0.1 | 0.3 | 0.2 | 38.5 |
| ENSI | Mix | Sorghum, Millet, and Sunflower mix | 16.5 | 14.9 | 0.90 | 406 | 10.9 | 3% | 87 | 19.1 | 43.1 | 0.1 | 6.0 | 0.0 | 2.3 | 0.0 | 0.3 | 0.0 | 38.8 |
| ENSI | Sorghum | Sucro variety | 15.5 | 14.3 | 0.92 | 351.3 | 8.5 | 2% | 79 | 25.1 | 42.6 | 0.3 | 6.0 | 0.0 | 1.7 | 0.0 | 0.2 | 0.0 | 41.8 |
| ENSI | Sorghum | Vega variety | 16.1 | 14.8 | 0.92 | 360.4 | 6.4 | 2% | 79 | 19.5 | 43.4 | 0.1 | 5.9 | 0.0 | 2.2 | 0.1 | 0.2 | 0.0 | 39.9 |
| ENSI | Mix | Vega sorghum variety and San Lucas sunflower variety | 21.5 | 19.1 | 0.89 | 286.9 | 17.1 | 6% | 67 | 25.3 | 41.5 | 0.1 | 5.3 | 0.1 | 1.6 | 0.2 | 0.3 | 0.1 | 40.4 |
| ENSI | Mix | Sunflower, Millet, and Guizotia abyssinica | 16.7 | 14.5 | 0.87 | 312.7 | 4.6 | 1% | 68 | 27.6 | 42.0 | 0.1 | 5.4 | 0.2 | 1.5 | 0.1 | 0.4 | 0.3 | 37.6 |
| ENSI | Mix | Sunflower, Millet, and Guizotia abyssinica | 17.6 | 15.7 | 0.89 | 318.4 | 0.9 | 0% | 69 | 30.4 | 42.8 | 0.2 | 5.5 | 0.0 | 1.4 | 0.1 | 0.2 | 0.1 | 39.1 |
| ENSI | Mix | — | 18.6 | 16.5 | 0.89 | 337.1 | 32.1 | 10% | 70 | 32.8 | 42.5 | 0.1 | 6.1 | 0.1 | 1.3 | 0.2 | 0.2 | 0.0 | 38.6 |
| ENSI | Millet and Clover | — | 15.9 | 14.1 | 0.89 | 374.1 | 1.7 | 0% | 85 | 26.6 | 40.6 | 0.0 | 5.8 | 0.2 | 1.5 | 0.3 | 0.2 | 0.0 | 40.6 |
| ENSI | Maize | — | 35.2 | 33.9 | 0.96 | 272.1 | 5 | 2% | 63 | 47.5 | 42.6 | 0.3 | 6.5 | 0.1 | 0.9 | 0.2 | 0.1 | 0.0 | 46.2 |
| ENSI | Mix | Residue | 23.3 | 22.9 | 0.98 | 371.5 | 16.9 | 5% | 81 | 62.4 | 45.5 | 0.2 | 6.6 | 0.1 | 0.7 | 0.1 | 0.1 | 0.0 | 45.1 |
| ENSI | Sorghum | Sucro variety | 31.3 | 29.9 | 0.96 | 332.7 | 21.5 | 6% | 79 | 73.8 | 43.5 | 0.3 | 5.8 | 0.0 | 0.6 | 0.0 | 0.2 | 0.0 | 45.6 |
| ENSI | Mix | Sorghum (Pacific graze), Millet (Robusta), Vetch (Bingo and Massa), and Clover (Tabor) | 26.6 | 23.9 | 0.90 | 269.4 | 3.3 | 1% | 64 | 27.1 | 40.3 | 0.0 | 5.7 | 0.1 | 1.5 | 0.1 | 0.2 | 0.0 | 42.4 |
| ENSI | Millet and Clover | — | 29.7 | 26.0 | 0.88 | 275.8 | 4.1 | 1% | 61 | 21.9 | 41.4 | 0.0 | 5.5 | 0.2 | 1.9 | 0.2 | 0.6 | 0.0 | 38.3 |

**Table A1.** *Cont.*

| **Family** | **Type** | **Sub Type** | **DM** | **VS** | **VS/DM** | **BMP exp** | | **CV(%)** | **Biodegradation** | **C/N** | **Carbon** | | **Hydrogen** | | **Nitrogen** | | **Sulfur** | | **Oxygen** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Mean** | **Mean** | **Mean** | **Mean** | **SD** | | | | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** |
| | | | | **(% FM)** | | **(Nm$^3$ CH$_4$/t VS)** | | | **%** | | **(% DM)** | | **(% DM)** | | **(% DM)** | | **(% DM)** | | **(% DM)** |
| ENSI | Millet and Clover | — | 27.1 | 24.9 | 0.92 | 303.7 | 17.3 | 6% | 69 | 23.3 | 42.6 | 0.2 | 5.8 | 0.2 | 1.8 | 0.2 | 0.3 | 0.2 | 41.3 |
| ENSI | Millet and Clover | — | 27.1 | 24.9 | 0.92 | 285.2 | 4 | 1% | 65 | 31.5 | 42.9 | 0.1 | 5.6 | 0.0 | 1.4 | 0.1 | 0.2 | 0.0 | 42.1 |
| ENSI | Sorghum | — | 19.8 | 18.0 | 0.91 | 285.6 | 2.1 | 1% | 64 | 54.5 | 41.8 | 0.0 | 6.0 | 0.1 | 0.8 | 0.1 | 0.1 | 0.0 | 42.2 |
| ENSI | Maize | — | 36.5 | 35.3 | 0.97 | 336 | 20.4 | 6% | 82 | 47.9 | 41.8 | 0.2 | 6.4 | 0.2 | 0.9 | 0.2 | 0.2 | 0.1 | 47.4 |
| ENSI | Rye and Vetch | — | 49.4 | 45.9 | 0.93 | 255.1 | 10.9 | 4% | 62 | 40.2 | 42.3 | 0.3 | 5.3 | 0.2 | 1.1 | 0.1 | 0.2 | 0.0 | 44.1 |
| ENSI | Rye and Vetch | — | 28.3 | 26.7 | 0.94 | 284.6 | 14.7 | 5% | 68 | 58.8 | 42.8 | 0.2 | 5.6 | 0.3 | 0.7 | 0.1 | 0.2 | 0.1 | 45.0 |
| ENSI | Mix | — | 28.9 | 25.8 | 0.89 | 368.7 | 4.3 | 1% | 81 | 57.0 | 41.8 | 0.2 | 5.8 | 0.1 | 0.7 | 0.1 | 0.2 | 0.0 | 40.7 |
| ENSI | Mix | Faba bean, Rye, and Radish | 20.3 | 18.8 | 0.92 | 300.1 | 0.7 | 0% | 72 | 29.4 | 42.0 | 0.2 | 5.5 | 0.0 | 1.4 | 0.1 | 0.2 | 0.0 | 43.2 |
| ENSI | Mix | Faba bean, Triticale, and Radish | 17.5 | 16.1 | 0.91 | 294.3 | 6.2 | 2% | 70 | 30.2 | 41.0 | 0.3 | 5.7 | 0.1 | 1.4 | 0.1 | 0.3 | 0.0 | 43.1 |
| ENSI | Mix | Grass | 54.6 | 46.6 | 0.85 | 253.9 | 14.4 | 6% | 55 | 25.7 | 39.7 | 0.2 | 5.8 | 0.1 | 1.5 | 0.2 | 0.3 | 0.0 | 37.9 |
| ENSI | Mix | Sorghum and Maize | 32.1 | 28.4 | 0.89 | 315.9 | 1.8 | 1% | 74 | 51.5 | 38.7 | 0.2 | 6.1 | 0.2 | 0.8 | 0.2 | 0.3 | 0.2 | 42.8 |
| ENSI | Mix | Peas, Vetch, Oats, and Beans | 27.0 | 24.5 | 0.91 | 331 | 15 | 5% | 67 | 20.6 | 45.0 | 0.0 | 6.1 | 0.0 | 2.2 | 0.2 | 0.2 | 0.0 | 37.4 |
| ENSI | Maize | — | 33.0 | 32.1 | 0.97 | 319.1 | 10.7 | 3% | 73 | 44.4 | 44.4 | 0.2 | 6.4 | 0.1 | 1.0 | 0.0 | 0.1 | 0.0 | 45.4 |
| ENSI | Sorghum | — | 35.9 | 33.1 | 0.92 | 272.6 | 3.7 | 1% | 62 | 51.7 | 43.9 | 0.3 | 5.3 | 0.1 | 0.8 | 0.0 | 0.2 | 0.2 | 42.0 |
| ENSI | Mix | Moha and Clover | 50.3 | 44.8 | 0.89 | 282.5 | 11.2 | 4% | 58 | 34.9 | 43.9 | 0.2 | 6.0 | 0.1 | 1.3 | 0.1 | 0.2 | 0.0 | 37.7 |
| ENSI | Rapeseed | — | 18.2 | 17.2 | 0.94 | 432.5 | 5.6 | 1% | 93 | 79.4 | 44.4 | 0.3 | 6.4 | 0.2 | 0.6 | 0.1 | 0.5 | 0.5 | 42.4 |
| ENSI | Grass | — | 27.8 | 24.7 | 0.89 | 264.3 | 15 | 6% | 57 | 25.2 | 41.5 | 0.2 | 6.1 | 0.1 | 1.6 | 0.2 | 0.2 | 0.0 | 39.3 |
| ENSI | Sorghum | — | 23.6 | 21.2 | 0.90 | 305.3 | 3 | 1% | 69 | 45.0 | 40.8 | 0.0 | 6.0 | 0.0 | 0.9 | 0.1 | 0.2 | 0.1 | 41.8 |
| ENSI | Sunflower | — | 15.6 | 14.1 | 0.90 | 290.7 | 0.9 | 0% | 63 | 44.1 | 41.7 | 0.2 | 6.3 | 0.0 | 0.9 | 0.1 | 0.2 | 0.0 | 41.2 |
| ENSI | Grass | — | 17.2 | 13.5 | 0.78 | 406.3 | 4.8 | 1% | 70 | 34.6 | 42.8 | 0.1 | 5.8 | 0.2 | 1.2 | 0.0 | 0.2 | 0.0 | 28.2 |
| ENSI | Maize | — | 28.5 | 27.2 | 0.96 | 376.3 | 31.1 | 8% | 89 | 43.3 | 43.1 | 0.1 | 5.9 | 0.3 | 1.0 | 0.1 | 0.1 | 0.0 | 45.4 |
| ENSI | Alfalfa | — | 69.0 | 62.4 | 0.90 | 271 | 0.1 | 0% | 60 | 26.7 | 42.9 | 0.2 | 5.7 | 0.0 | 1.6 | 0.1 | 0.2 | 0.0 | 40.0 |
| ENSI | Sorghum | — | 24.7 | 23.3 | 0.94 | 289.8 | 10.9 | 4% | 67 | 43.3 | 43.6 | 0.1 | 5.8 | 0.1 | 1.0 | 0.1 | 0.2 | 0.1 | 43.7 |
| ENSI | Grass | Ray-grass | 17.6 | 16.7 | 0.95 | 393.3 | 26.5 | 7% | 87 | 66.5 | 44.5 | 0.0 | 6.0 | 0.0 | 0.7 | 0.1 | 0.2 | 0.1 | 43.1 |
| ENSI | Maize | — | 19.8 | 19.4 | 0.98 | 418 | 4.2 | 1% | 90 | 42.1 | 46.8 | 0.1 | 6.3 | 0.1 | 1.1 | 0.1 | 0.2 | 0.1 | 43.4 |

**Table A1.** *Cont.*

| Family | Type | Sub Type | DM | VS | VS/DM | BMP exp | | CV(%) | Biodegradation | C/N | Carbon | | Hydrogen | | Nitrogen | | Sulfur | | Oxygen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | Mean | Mean | Mean | SD | | | | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean |
| | | | | (% FM) | | (Nm$^3$ CH$_4$/t VS) | | | % | | (% DM) | | (% DM) | | (% DM) | | (% DM) | | (% DM) |
| ENSI | Grass | — | 21.3 | 18.9 | 0.89 | 461.2 | 3.7 | 1% | 100 | 23.8 | 41.4 | 0.2 | 5.9 | 0.0 | 1.7 | 0.0 | 0.4 | 0.1 | 39.2 |
| ENSI | Maize | — | 33.6 | 32.4 | 0.96 | 383.9 | 1.5 | 0% | 85 | 45.6 | 44.6 | 0.2 | 6.4 | 0.2 | 1.0 | 0.1 | 0.1 | 0.0 | 44.4 |
| ENSI | Maize | — | 30.2 | 28.8 | 0.95 | 335.1 | 10 | 3% | 75 | 42.2 | 43.6 | 0.2 | 6.5 | 0.1 | 1.0 | 0.1 | 0.1 | 0.0 | 43.9 |
| ENSI | Grass | — | 23.4 | 21.3 | 0.91 | 403.2 | 14.2 | 4% | 90 | 29.3 | 42.9 | 0.2 | 5.7 | 0.1 | 1.5 | 0.2 | 0.3 | 0.0 | 40.8 |
| ENSI | Grass | — | 39.9 | 36.1 | 0.91 | 187.2 | 11.5 | 6% | 40 | 49.5 | 42.4 | 0.3 | 6.4 | 0.1 | 0.9 | 0.0 | 0.3 | 0.0 | 40.6 |
| ENSI | Maize | — | 32.0 | 30.3 | 0.95 | 301.1 | 7.4 | 2% | 71 | 37.7 | 42.2 | 0.1 | 6.2 | 0.1 | 1.1 | 0.2 | 0.3 | 0.0 | 44.9 |
| MAN | Mix | Manure and Spates | 32.1 | 17.3 | 0.54 | 253.4 | 14.9 | 6% | 38 | 27.2 | 31.7 | 0.1 | 4.4 | 0.2 | 1.2 | 0.1 | 0.4 | 0.0 | 16.2 |
| MAN | Cattle | After phase separation, Straw | 15.3 | 13.8 | 0.90 | 321.9 | 16.8 | 5% | 80 | 15.8 | 39.8 | 0.0 | 5.4 | 0.0 | 2.5 | 0.1 | 0.5 | 0.0 | 41.8 |
| MAN | Horse | — | 8.0 | 5.3 | 0.66 | 237.6 | 14.3 | 6% | 42 | 22.4 | 35.8 | 0.1 | 5.0 | 0.2 | 1.6 | 0.1 | 0.3 | 0.0 | 23.8 |
| MAN | Cattle | Straw | 27.7 | 25.1 | 0.91 | 257.7 | 14.9 | 6% | 63 | 45.9 | 40.3 | 0.2 | 5.5 | 0.2 | 0.9 | 0.1 | 0.2 | 0.0 | 43.7 |
| MAN | Cattle | Straw | 16.6 | 14.3 | 0.86 | 236 | 21.7 | 9% | 51 | 30.7 | 41.8 | 0.1 | 5.3 | 0.3 | 1.4 | 0.0 | 0.2 | 0.1 | 37.8 |
| MAN | Cattle | Fern | 27.6 | 24.1 | 0.87 | 162 | 5.7 | 4% | 33 | 32.6 | 43.2 | 0.3 | 5.6 | 0.0 | 1.3 | 0.2 | 0.2 | 0.0 | 36.9 |
| MAN | Cattle | Straw | 43.1 | 34.5 | 0.80 | 191.3 | 8.4 | 4% | 39 | 54.2 | 40.6 | 0.1 | 4.8 | 0.2 | 0.7 | 0.1 | 1.4 | 0.3 | 32.7 |
| MAN | Horse | — | 81.6 | 69.1 | 0.85 | 258.2 | 11.9 | 5% | 57 | 49.6 | 40.8 | 0.1 | 5.1 | 0.2 | 0.8 | 0.1 | 0.8 | 0.1 | 37.1 |
| MAN | Poultry | — | 57.2 | 35.3 | 0.62 | 216.8 | 6.9 | 3% | 49 | 12.0 | 28.7 | 0.3 | 4.0 | 0.3 | 2.4 | 0.0 | 0.4 | 0.1 | 26.2 |
| MAN | Poultry | — | 75.9 | 58.0 | 0.76 | 263.8 | 1.9 | 1% | 63 | 15.3 | 34.7 | 0.3 | 4.7 | 0.2 | 2.3 | 0.0 | 0.6 | 0.1 | 34.3 |
| MAN | Pig | — | 31.6 | 27.0 | 0.85 | 217.8 | 13.5 | 6% | 50 | 19.5 | 38.8 | 0.1 | 5.6 | 0.1 | 2.0 | 0.3 | 0.4 | 0.0 | 38.7 |
| MAN | Cattle | Straw, after 1 month conservation | 17.0 | 13.0 | 0.76 | 198.6 | 17.3 | 9% | 38 | 29.2 | 39.5 | 0.1 | 5.3 | 0.0 | 1.4 | 0.3 | 0.7 | 0.2 | 29.7 |
| MAN | Turkey | — | 68.3 | 52.3 | 0.77 | 173 | 1.1 | 1% | 37 | 13.5 | 36.6 | 0.2 | 5.1 | 0.1 | 2.7 | 0.3 | 0.5 | 0.0 | 31.6 |
| MAN | Mix | — | 15.3 | 13.8 | 0.90 | 243.3 | 1 | 0% | 56 | 21.4 | 40.9 | 0.1 | 5.9 | 0.0 | 1.9 | 0.0 | 0.3 | 0.0 | 40.9 |
| MAN | Poultry | — | 71.2 | 58.3 | 0.82 | 211 | 16.1 | 8% | 49 | 8.2 | 36.7 | 0.2 | 5.6 | 0.1 | 4.5 | 0.1 | 0.6 | 0.0 | 34.4 |
| MAN | Poultry | — | 60.3 | 50.4 | 0.84 | 274.1 | 13 | 5% | 69 | 15.5 | 35.3 | 0.0 | 5.6 | 0.1 | 2.3 | 0.3 | 1.0 | 0.2 | 39.5 |
| MAN | Cattle | Straw | 45.6 | 34.2 | 0.75 | 131.9 | 1.4 | 1% | 21 | 51.3 | 43.5 | 0.3 | 5.8 | 0.0 | 0.8 | 0.3 | 0.3 | 0.0 | 24.6 |
| MAN | Horse | — | 20.2 | 16.4 | 0.81 | 182.6 | 9.9 | 5% | 41 | 27.5 | 39.5 | 0.0 | 4.5 | 0.2 | 1.4 | 0.0 | 0.5 | 0.0 | 35.2 |
| MAN | Cattle | Straw | 69.8 | 61.7 | 0.88 | 233.2 | 15.3 | 7% | 55 | 34.0 | 40.6 | 0.3 | 5.2 | 0.0 | 1.2 | 0.2 | 0.6 | 0.1 | 40.9 |
| MAN | Poultry | — | 49.6 | 40.5 | 0.82 | 185.6 | 8.8 | 5% | 42 | 15.3 | 37.7 | 0.2 | 5.4 | 0.1 | 2.5 | 0.2 | 0.7 | 0.0 | 35.4 |
| MAN | Horse | — | 34.4 | 29.1 | 0.85 | 308.4 | 15.3 | 5% | 65 | 55.3 | 40.9 | 0.0 | 5.5 | 0.0 | 0.7 | 0.1 | 0.4 | 0.1 | 37.1 |
| MAN | Horse | — | 33.2 | 27.0 | 0.81 | 281.2 | 16.2 | 6% | 57 | 79.1 | 39.6 | 0.3 | 5.6 | 0.2 | 0.5 | 0.0 | 0.3 | 0.1 | 35.3 |
| MAN | Zoo | — | 31.3 | 25.5 | 0.81 | 235.3 | 10.7 | 5% | 51 | 30.8 | 38.7 | 0.3 | 5.3 | 0.2 | 1.3 | 0.3 | 0.3 | 0.1 | 35.6 |
| MAN | Cattle | Straw | 22.8 | 20.1 | 0.88 | 166.9 | 7.3 | 4% | 38 | 39.2 | 41.2 | 0.2 | 5.5 | 0.1 | 1.1 | 0.1 | 0.3 | 0.1 | 40.1 |

**Table A1.** *Cont.*

| Family | Type | Sub Type | DM | VS | VS/DM | BMP exp | | CV(%) | Biodegradation | C/N | Carbon | | Hydrogen | | Nitrogen | | Sulfur | | Oxygen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | Mean | Mean | Mean | SD | | | | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean |
| | | | (% FM) | | | (Nm$^3$ CH$_4$/t VS) | | | % | | (% DM) | | (% DM) | | (% DM) | | (% DM) | | (% DM) |
| MAN | Mix | Straw | 22.3 | 19.4 | 0.87 | 346.9 | 15.9 | 5% | 73 | 18.6 | 41.1 | 0.1 | 6.1 | 0.2 | 2.2 | 0.1 | 0.3 | 0.1 | 37.2 |
| MAN | Mix | Straw | 20.9 | 18.1 | 0.86 | 366 | 7.1 | 2% | 72 | 20.1 | 42.8 | 0.0 | 6.2 | 0.1 | 2.1 | 0.3 | 0.3 | 0.1 | 35.0 |
| MAN | Horse | — | 57.6 | 50.3 | 0.87 | 281.1 | 10 | 4% | 62 | 62.4 | 40.7 | 0.1 | 5.7 | 0.2 | 0.7 | 0.1 | 0.5 | 0.0 | 39.8 |
| MAN | Horse | — | 51.0 | 44.8 | 0.88 | 240.9 | 13.6 | 6% | 57 | 75.1 | 39.3 | 0.2 | 5.6 | 0.2 | 0.5 | 0.1 | 0.6 | 0.2 | 41.8 |
| MAN | Cattle | Straw | 43.1 | 34.5 | 0.80 | 191.4 | 8.3 | 4% | 46 | 17.2 | 35.0 | 0.2 | 5.3 | 0.0 | 2.0 | 0.3 | 0.5 | 0.0 | 37.3 |
| MAN | Cattle | Straw | 33.7 | 27.9 | 0.83 | 223.8 | 9 | 4% | 49 | 21.2 | 38.4 | 0.1 | 5.8 | 0.0 | 1.8 | 0.1 | 0.4 | 0.0 | 36.6 |
| MAN | Horse | — | 31.5 | 26.0 | 0.83 | 250.6 | 18.6 | 7% | 60 | 13.5 | 36.2 | 0.0 | 5.6 | 0.1 | 2.7 | 0.3 | 0.6 | 0.0 | 37.3 |
| CER | Maize Residues | Follicle | 73.9 | 71.7 | 0.97 | 279.2 | 19 | 7% | 64 | 33.1 | 43.1 | 0.2 | 6.8 | 0.1 | 1.3 | 0.0 | 0.2 | 0.0 | 45.6 |
| CER | Wheat | Contaminated culture | 86.2 | 84.0 | 0.97 | 317.7 | 2.1 | 1% | 78 | 22.9 | 41.2 | 0.1 | 6.8 | 0.0 | 1.8 | 0.1 | 0.2 | 0.0 | 47.4 |
| CER | Mix | Cereals | 75.6 | 72.5 | 0.96 | 285.9 | 15.8 | 6% | 64 | 29.4 | 43.0 | 0.3 | 6.7 | 0.1 | 1.5 | 0.0 | 0.1 | 0.0 | 44.5 |
| CER | Mix | Cereal dust | 89.4 | 80.1 | 0.90 | 300.1 | 5.6 | 2% | 66 | 42.6 | 41.9 | 0.0 | 5.8 | 0.1 | 1.0 | 0.1 | 0.1 | 0.0 | 40.8 |
| CER | Mix | Cereal residue | 72.0 | 64.7 | 0.90 | 250.2 | 9.3 | 4% | 57 | 11.4 | 40.6 | 0.3 | 6.2 | 0.1 | 3.6 | 0.2 | 0.3 | 0.0 | 39.2 |
| CER | Maize | Fresh residue from sweet corn | 24.6 | 24.2 | 0.98 | 314 | 20 | 6% | 77 | 53.1 | 43.5 | 0.2 | 6.0 | 0.1 | 0.8 | 0.0 | 0.1 | 0.0 | 47.9 |
| CER | Maize | Fresh residue from sweet corn | 21.9 | 21.4 | 0.98 | 262.7 | 0.1 | 0% | 63 | 43.3 | 43.5 | 0.2 | 6.2 | 0.1 | 1.0 | 0.0 | 0.2 | 0.1 | 46.6 |
| CER | Maize | Fresh residue from sweet corn | 23.9 | 23.3 | 0.97 | 306 | 5.4 | 2% | 71 | 43.7 | 43.8 | 0.0 | 6.4 | 0.1 | 1.0 | 0.1 | 0.1 | 0.0 | 46.3 |
| CER | Maize | Fresh residue from sweet corn | 26.7 | 26.3 | 0.99 | 335.5 | 5.4 | 2% | 78 | 49.6 | 44.6 | 0.2 | 6.3 | 0.0 | 0.9 | 0.1 | 0.1 | 0.0 | 46.5 |
| CER | Maize | Fresh residue from sweet corn | 23.6 | 23.1 | 0.98 | 312.3 | 14 | 4% | 69 | 36.9 | 44.6 | 0.2 | 6.7 | 0.1 | 1.2 | 0.0 | 0.6 | 0.2 | 44.7 |
| CER | Maize | Fresh residue from sweet corn | 21.9 | 21.4 | 0.98 | 263.7 | 24.5 | 9% | 60 | 57.8 | 44.0 | 0.3 | 6.7 | 0.0 | 0.8 | 0.2 | 0.04 | 0.1 | 46.4 |
| CER | Maize | Fresh residue from sweet corn | 26.5 | 26.0 | 0.98 | 306.8 | 5.2 | 2% | 71 | 56.7 | 43.7 | 0.3 | 6.7 | 0.1 | 0.8 | 0.2 | 0.1 | 0.1 | 46.9 |
| CER | Mix | Cereals | 87.0 | 80.6 | 0.93 | 313.3 | 7.8 | 2% | 67 | 12.1 | 43.3 | 0.0 | 6.7 | 0.0 | 3.6 | 0.3 | 0.2 | 0.0 | 38.9 |
| CER | Maize | Flour | 87.0 | 85.4 | 0.98 | 325.4 | 28.8 | 9% | 80 | 37.8 | 41.4 | 0.2 | 6.8 | 0.0 | 1.1 | 0.1 | 0.1 | 0.0 | 48.8 |
| CER | Mix | Cereals | 77.0 | 71.9 | 0.93 | 328.4 | 7.2 | 2% | 73 | 18.3 | 43.2 | 0.1 | 6.4 | 0.1 | 2.4 | 0.2 | 0.2 | 0.0 | 41.3 |
| CER | Mix | Silo’s lose | 79.8 | 74.1 | 0.93 | 320.4 | 14.7 | 5% | 77 | 56.2 | 40.2 | 0.0 | 6.2 | 0.0 | 0.7 | 0.1 | 0.3 | 0.0 | 45.4 |

**Table A1.** *Cont.*

| Family | Type | Sub Type | DM | VS | VS/DM | BMP exp | | CV(%) | Biodegradation | C/N | Carbon | | Hydrogen | | Nitrogen | | Sulfur | | Oxygen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | Mean | Mean | Mean | SD | | | | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean |
| | | | (% FM) | | | (Nm$^3$ CH$_4$/t VS) | | | % | | (% DM) | | (% DM) | | (% DM) | | (% DM) | | (% DM) |
| CER | Mix | Cereals | 75.6 | 72.5 | 0.96 | 285.9 | 15.8 | 6% | 66 | 29.8 | 42.4 | 0.1 | 6.7 | 0.1 | 1.4 | 0.1 | 0.3 | 0.0 | 44.9 |
| SLU | Cattle | — | 4.7 | 3.5 | 0.74 | 291 | 3 | 1% | 51 | 15.7 | 40.5 | 0.2 | 5.4 | 0.1 | 2.6 | 0.1 | 0.5 | 0.0 | 25.6 |
| SLU | Rabbit | — | 18.4 | 15.9 | 0.86 | 263.8 | 4.7 | 2% | 55 | 24.1 | 41.6 | 0.2 | 5.9 | 0.0 | 1.7 | 0.1 | 0.5 | 0.1 | 36.7 |
| SLU | Cattle | — | 26.3 | 24.2 | 0.92 | 224.1 | 3.7 | 2% | 70 | 16.0 | 35.9 | 0.2 | 5.1 | 0.1 | 2.2 | 0.2 | 0.6 | 0.0 | 48.0 |
| SLU | Duck | — | 6.2 | 5.2 | 0.84 | 551.2 | 26.3 | 5% | 100 | 14.2 | 42.1 | 0.2 | 6.1 | 0.1 | 3.0 | 0.2 | 0.4 | 0.1 | 31.9 |
| SLU | Cattle | — | 10.4 | 8.1 | 0.78 | 481 | 10.2 | 2% | 91 | 27.3 | 39.5 | 0.1 | 5.8 | 0.0 | 1.4 | 0.3 | 0.5 | 0.2 | 30.6 |
| LCM | Maize Residue | Cob | 28.4 | 27.7 | 0.98 | 272.2 | 2.1 | 1% | 63 | 497.8 | 44.1 | 0.2 | 6.3 | 0.1 | 0.1 | 0.0 | 0.1 | 0.1 | 47.2 |
| LCM | Hemp | Dust | 88.1 | 69.0 | 0.78 | 184.4 | 4.5 | 2% | 36 | 48.5 | 39.6 | 0.1 | 5.3 | 0.0 | 0.8 | 0.0 | 0.2 | 0.0 | 32.5 |
| LCM | Straw | Plant residues | 88.0 | 83.9 | 0.95 | 277.6 | 7.6 | 3% | 68 | 60.0 | 42.2 | 0.0 | 5.8 | 0.1 | 0.7 | 0.1 | 0.3 | 0.0 | 46.4 |
| LCM | Straw | — | 87.6 | 84.6 | 0.97 | 274.1 | 2.2 | 1% | 67 | 77.8 | 42.7 | 0.1 | 6.0 | 0.0 | 0.5 | 0.0 | 0.3 | 0.1 | 47.1 |
| LCM | Maize | Beans | 42.0 | 36.4 | 0.87 | 246.8 | 13.3 | 5% | 51 | 165.7 | 42.8 | 0.1 | 5.5 | 0.3 | 0.3 | 0.1 | 0.8 | 0.1 | 37.3 |
| LCM | Bagasse and Straw | — | 52.2 | 48.3 | 0.92 | 188.1 | 9.1 | 5% | 42 | 245.9 | 43.3 | 0.1 | 5.7 | 0.2 | 0.2 | 0.1 | 0.3 | 0.1 | 43.0 |
| LCM | Bagasse | — | 43.2 | 40.9 | 0.95 | 173.7 | 7.2 | 4% | 39 | 376.8 | 44.6 | 0.2 | 5.9 | 0.2 | 0.1 | 0.0 | 0.2 | 0.1 | 44.0 |
| LCM | Straw | — | 54.0 | 47.5 | 0.88 | 199.8 | 8.8 | 4% | 42 | 193.6 | 43.4 | 0.1 | 5.4 | 0.2 | 0.2 | 0.0 | 0.2 | 0.0 | 38.7 |
| LCM | Bagasse | — | 56.7 | 41.2 | 0.73 | 250.6 | 16.5 | 7% | 39 | 297.1 | 42.8 | 0.2 | 5.5 | 0.2 | 0.1 | 0.0 | 0.1 | 0.0 | 24.1 |
| LCM | Straw | Waste | 79.2 | 71.8 | 0.91 | 329.8 | 0.8 | 0% | 72 | 79.1 | 42.8 | 0.1 | 5.8 | 0.0 | 0.5 | 0.1 | 0.2 | 0.1 | 41.4 |
| LCM | Green waste | — | 37.9 | 35.2 | 0.93 | 212.1 | 1.8 | 1% | 47 | 136.8 | 43.4 | 0.0 | 5.8 | 0.1 | 0.3 | 0.1 | 0.6 | 0.1 | 42.7 |
| LCM | Straw | — | 86.5 | 82.2 | 0.95 | 277.6 | 21.8 | 8% | 67 | 64.0 | 43.0 | 0.3 | 5.7 | 0.1 | 0.7 | 0.1 | 0.1 | 0.0 | 45.5 |
| LCM | Hay | Meadow | 86.0 | 80.4 | 0.93 | 289 | 7.1 | 2% | 65 | 51.4 | 42.6 | 0.1 | 6.3 | 0.0 | 0.8 | 0.1 | 0.1 | 0.0 | 43.7 |
| LCM | Straw | Plant residues | 89.0 | 85.1 | 0.96 | 292.7 | 27.4 | 9% | 70 | 89.0 | 42.5 | 0.1 | 6.1 | 0.3 | 0.5 | 0.0 | 0.2 | 0.2 | 46.4 |
| LCM | Straw | Plant residues | 87.2 | 83.2 | 0.95 | 298.9 | 2.3 | 1% | 69 | 89.3 | 42.9 | 0.1 | 6.2 | 0.1 | 0.5 | 0.0 | 0.1 | 0.1 | 45.6 |
| LCM | Straw | — | 88.3 | 84.0 | 0.95 | 302.1 | 5.9 | 2% | 72 | 73.6 | 42.3 | 0.2 | 6.0 | 0.3 | 0.6 | 0.1 | 0.3 | 0.3 | 46.0 |
| LCM | Straw | — | 88.8 | 86.0 | 0.97 | 290.6 | 7.1 | 2% | 69 | 132.0 | 43.0 | 0.1 | 6.3 | 0.0 | 0.3 | 0.0 | 0.1 | 0.0 | 47.1 |
| LCM | Straw | — | 75.9 | 70.4 | 0.93 | 305.5 | 6.4 | 2% | 70 | 102.2 | 42.9 | 0.0 | 5.7 | 0.1 | 0.4 | 0.0 | 0.2 | 0.0 | 43.5 |
| LCM | Straw | Waste | 84.9 | 81.3 | 0.96 | 293.7 | 1 | 0% | 67 | 126.8 | 44.2 | 0.2 | 5.9 | 0.0 | 0.3 | 0.0 | 0.1 | 0.0 | 45.2 |
| LCM | Flower residue | Lavender | 88.7 | 81.2 | 0.92 | 200.5 | 9.6 | 5% | 42 | 41.5 | 45.0 | 0.1 | 6.0 | 0.0 | 1.1 | 0.2 | 0.3 | 0.1 | 39.3 |
| LCM | Maize | Leaf | 37.8 | 35.0 | 0.93 | 286.3 | 23.3 | 8% | 65 | 56.5 | 43.2 | 0.1 | 5.8 | 0.0 | 0.8 | 0.0 | 0.1 | 0.0 | 42.8 |
| LCM | Straw | Plant residues | 86.3 | 82.3 | 0.95 | 280.5 | 2.9 | 1% | 69 | 68.3 | 41.5 | 0.3 | 6.0 | 0.1 | 0.6 | 0.1 | 0.2 | 0.1 | 47.1 |

**Table A1.** *Cont.*

| Family | Type | Sub Type | DM | VS | VS/DM | BMP exp | | CV(%) | Biodegradation | C/N | Carbon | | Hydrogen | | Nitrogen | | Sulfur | | Oxygen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | Mean | Mean | Mean | SD | | | | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean |
| | | | | (% FM) | | ($Nm^3$ $CH_4$/t VS) | | | % | | (% DM) | | (% DM) | | (% DM) | | (% DM) | | (% DM) |
| LCM | Straw | Waste | 84.5 | 77.3 | 0.92 | 306 | 23.1 | 8% | 66 | 128.8 | 43.5 | 0.3 | 5.9 | 0.0 | 0.3 | 0.0 | 0.1 | 0.0 | 41.7 |
| LCM | Straw | Rapeseed waste | 71.9 | 62.9 | 0.87 | 241.4 | 3 | 1% | 54 | 31.1 | 40.0 | 0.2 | 5.8 | 0.2 | 1.3 | 0.0 | 0.4 | 0.2 | 40.0 |
| LCM | Straw | — | 85.0 | 81.2 | 0.96 | 309.7 | 10.1 | 3% | 72 | 162.8 | 43.8 | 0.3 | 5.9 | 0.0 | 0.3 | 0.1 | 0.1 | 0.0 | 45.6 |
| LCM | Straw | Waste | 83.9 | 78.2 | 0.93 | 283.8 | 8.8 | 3% | 62 | 119.4 | 43.6 | 0.1 | 6.3 | 0.0 | 0.4 | 0.2 | 0.2 | 0.1 | 42.8 |
| LCM | Green waste | — | 44.6 | 34.5 | 0.77 | 178.2 | 0.1 | 0% | 33 | 23.9 | 40.3 | 0.1 | 5.5 | 0.1 | 1.7 | 0.2 | 0.1 | 0.0 | 29.7 |
| LCM | Mix | Green waste | 34.4 | 26.4 | 0.77 | 218.9 | 11.6 | 5% | 45 | 21.9 | 37.5 | 0.3 | 5.3 | 0.2 | 1.7 | 0.1 | 0.2 | 0.0 | 31.9 |
| LCM | Green waste | — | 80.6 | 36.9 | 0.46 | 63.1 | 3.4 | 5% | 7 | 29.2 | 34.5 | 0.0 | 4.5 | 0.0 | 1.2 | 0.2 | 0.3 | 0.0 | 5.3 |
| LCM | Flower residue | Pomace | 47.1 | 39.6 | 0.84 | 281.1 | 1.7 | 1% | 64 | 17.6 | 38.3 | 0.1 | 5.5 | 0.0 | 2.2 | 0.1 | 0.6 | 0.0 | 37.3 |
| LCM | Straw | — | 90.6 | 85.8 | 0.95 | 240 | 6.3 | 3% | 60 | 406.3 | 41.2 | 0.3 | 5.7 | 0.3 | 0.1 | 0.0 | 0.8 | 0.3 | 46.9 |
| LCM | Flower residue | Lavender | 82.8 | 78.2 | 0.94 | 171.3 | 12.4 | 7% | 37 | 68.8 | 44.3 | 0.0 | 6.3 | 0.0 | 0.6 | 0.3 | 0.6 | 0.1 | 42.6 |
| LCM | Straw | Waste | 88.8 | 82.3 | 0.93 | 267 | 7.4 | 3% | 64 | 263.7 | 40.3 | 0.1 | 6.1 | 0.3 | 0.2 | 0.1 | 0.8 | 0.1 | 45.3 |

**Table A2.** Description of the substrates analyzed within the families: fibers, protein content, and COD, where SD is standard deviation, DM is dry matter, VS is volatile solids, and COD is the chemical oxygen demand.

| **Family** | **Type** | **Sub Type** | **Cellulose** | | **Hemicelluloses** | | **Lignin** | | **Protein** | **COD** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Calculated** | **Calculated** |
| | | | **(g/100g DM)** | | **(g/100g DM)** | | **(g/100g DM)** | | **(% DM)** | **(g COD/g CxHyOz)** |
| ENSI | Millet | — | 28.6 | 1.4 | 17.7 | 1.1 | 22.3 | 0.3 | 4.9 | 1.3 |
| ENSI | Sorghum | — | 21.7 | 0.0 | 10.8 | 0.2 | 21.1 | 0.3 | 9.4 | 1.4 |
| ENSI | Mix | Sorghum, Millet, and Sunflower mix | 22.7 | 0.3 | 12.7 | 0.2 | 19.4 | 0.1 | 14.1 | 1.4 |
| ENSI | Sorghum | Sucro variety | 25.1 | 0.5 | 12.1 | 0.6 | 18.1 | 0.1 | 10.6 | 1.3 |
| ENSI | Sorghum | Vega variety | 22.8 | 0.7 | 13.7 | 0.4 | 20.0 | 0.9 | 13.9 | 1.4 |
| ENSI | Mix | Vega sorghum variety and San Lucas sunflower variety | 24.7 | 0.2 | 10.1 | 0.1 | 26.7 | 0.7 | 10.3 | 1.3 |
| ENSI | Mix | Sunflower, Millet, and Guizotia abyssinica | 17.3 | 0.3 | 7.1 | 0.1 | 26.6 | 1.3 | 9.5 | 1.4 |
| ENSI | Mix | Sunflower, Millet, and Guizotia abyssinica | 17.9 | 0.1 | 8.6 | 0.2 | 25.6 | 0.3 | 8.8 | 1.4 |
| ENSI | Mix | — | 22.6 | 0.8 | 9.2 | 0.2 | 25.1 | 0.3 | 8.1 | 1.4 |
| ENSI | Millet and Clover | — | 29.6 | 0.2 | 19.1 | 0.3 | 19.6 | 0.5 | 9.5 | 1.3 |
| ENSI | Maize | — | 47.7 | 1.5 | 11.5 | 0.5 | 11.4 | 0.2 | 5.6 | 1.3 |
| ENSI | Mix | Residue | 13.5 | 0.3 | 9.0 | 0.2 | 14.0 | 0.1 | 4.6 | 1.3 |
| ENSI | Sorghum | Sucro variety | 31.4 | 0.4 | 18.0 | 0.5 | 17.8 | 0.1 | 3.7 | 1.2 |
| ENSI | Mix | Sorghum (Pacific graze), Millet (Robusta), Vetch (Bingo and Massa), and Clover (Tabor) | 30.3 | 2.5 | 14.2 | 0.5 | 19.7 | 0.8 | 9.3 | 1.3 |
| ENSI | Millet and Clover | — | 22.4 | 0.4 | 15.4 | 0.3 | 22.2 | 1.0 | 11.8 | 1.4 |
| ENSI | Millet and Clover | — | 12.9 | 0.4 | 6.6 | 0.1 | 18.6 | 1.8 | 11.4 | 1.3 |
| ENSI | Millet and Clover | — | 11.2 | 0.1 | 6.4 | 0.1 | 21.0 | 0.2 | 8.5 | 1.3 |
| ENSI | Sorghum | — | 28.3 | 0.6 | 17.2 | 0.4 | 18.7 | 0.1 | 4.8 | 1.3 |
| ENSI | Maize | — | 49.9 | 0.6 | 12.6 | 0.4 | 11.4 | 0.2 | 5.5 | 1.2 |
| ENSI | Rye and Vetch | — | 25.8 | 0.0 | 15.1 | 0.0 | 22.1 | 0.1 | 6.6 | 1.2 |
| ENSI | Rye and Vetch | — | 26.7 | 0.0 | 17.4 | 0.0 | 20.6 | 0.1 | 4.5 | 1.2 |
| ENSI | Mix | — | 22.3 | 0.4 | 13.3 | 0.5 | 19.5 | 0.4 | 4.6 | 1.3 |
| ENSI | Mix | Faba bean, Rye, and Radish | 19.6 | 0.6 | 10.6 | 0.1 | 22.4 | 0.1 | 8.9 | 1.2 |
| ENSI | Mix | Faba bean, Triticale, and Radish | 17.5 | 0.0 | 8.8 | 0.0 | 18.1 | 0.2 | 8.5 | 1.2 |
| ENSI | Mix | Grass | 21.7 | 0.0 | 12.3 | 0.0 | 28.9 | 0.5 | 9.6 | 1.4 |
| ENSI | Mix | Sorghum and Maize | 22.0 | 0.5 | 15.4 | 0.3 | 17.8 | 0.3 | 4.7 | 1.2 |
| ENSI | Mix | Peas, Vetch, Oats, and Beans | 21.9 | 0.3 | 10.7 | 0.3 | 20.2 | 0.8 | 13.7 | 1.5 |
| ENSI | Maize | — | 45.5 | 1.0 | 10.5 | 0.3 | 13.3 | 0.4 | 6.2 | 1.3 |
| ENSI | Sorghum | — | 30.5 | 0.6 | 20.5 | 0.2 | 24.5 | 0.5 | 5.3 | 1.3 |
| ENSI | Mix | Moha and Clover | 28.4 | 0.1 | 13.5 | 0.5 | 19.2 | 1.0 | 7.9 | 1.5 |

**Table A2.** *Cont.*

| Family | Type | Sub Type | Cellulose | | Hemicelluloses | | Lignin | | Protein | COD |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | SD | Mean | SD | Mean | SD | Calculated | Calculated |
| | | | (g/100g DM) | | (g/100g DM) | | (g/100g DM) | | (% DM) | (g COD/g CxHyOz) |
| ENSI | Rapeseed | — | 25.7 | 1.2 | 10.2 | 1.0 | 27.4 | 0.3 | 3.5 | 1.4 |
| ENSI | Grass | — | 21.5 | 0.5 | 11.7 | 0.2 | 27.1 | 0.2 | 10.3 | 1.4 |
| ENSI | Sorghum | — | 31.6 | 0.2 | 14.0 | 0.1 | 22.9 | 0.3 | 5.7 | 1.3 |
| ENSI | Sunflower | — | 20.9 | 0.4 | 9.1 | 0.2 | 22.8 | 0.8 | 5.9 | 1.4 |
| ENSI | Grass | — | 29.9 | 0.2 | 16.9 | 0.2 | 25.7 | 1.6 | 7.7 | 1.7 |
| ENSI | Maize | — | 41.1 | 0.4 | 11.7 | 0.8 | 16.5 | 0.8 | 6.2 | 1.2 |
| ENSI | Alfalfa | — | 23.6 | 0.7 | 9.2 | 0.1 | 21.5 | 0.6 | 10.1 | 1.4 |
| ENSI | Sorghum | — | 29.8 | 0.3 | 13.1 | 0.8 | 16.8 | 0.4 | 6.3 | 1.3 |
| ENSI | Grass | Ray-grass | 31.9 | 1.6 | 14.1 | 0.9 | 21.9 | 1.6 | 4.2 | 1.3 |
| ENSI | Maize | — | 27.3 | 0.2 | 18.4 | 0.1 | 20.0 | 0.7 | 6.9 | 1.4 |
| ENSI | Grass | — | 24.9 | 0.2 | 14.8 | 0.5 | 19.5 | 0.3 | 10.9 | 1.4 |
| ENSI | Maize | — | 52.3 | 3.5 | 11.2 | 0.9 | 15.4 | 0.6 | 6.1 | 1.3 |
| ENSI | Maize | — | 41.3 | 1.2 | 9.6 | 0.4 | 13.1 | 1.3 | 6.5 | 1.3 |
| ENSI | Grass | — | 21.1 | 0.7 | 9.7 | 0.2 | 18.1 | 0.7 | 9.1 | 1.3 |
| ENSI | Grass | — | 26.0 | 0.4 | 13.7 | 0.3 | 18.4 | 1.1 | 5.3 | 1.4 |
| ENSI | Maize | — | 37.1 | 0.5 | 11.6 | 0.0 | 19.9 | 1.3 | 7.0 | 1.3 |
| MAN | Mix | Manure and Spates | 28.7 | 0.8 | 14.8 | 0.4 | 52.3 | 2.9 | 7.3 | 2.0 |
| MAN | Cattle | After phase separation, Straw | 24.5 | 0.6 | 17.5 | 0.5 | 26.0 | 0.7 | 15.7 | 1.2 |
| MAN | Horse | — | 25.3 | 2.5 | 14.2 | 0.6 | 48.7 | 2.2 | 10.0 | 1.7 |
| MAN | Cattle | Straw | 25.6 | 0.1 | 18.2 | 0.2 | 29.4 | 1.0 | 5.5 | 1.2 |
| MAN | Cattle | Straw | 22.5 | 1.8 | 15.3 | 0.0 | 34.9 | 0.6 | 8.5 | 1.4 |
| MAN | Cattle | Fern | 20.0 | 0.7 | 14.5 | 1.1 | 36.3 | 1.2 | 8.3 | 1.4 |
| MAN | Cattle | Straw | 29.2 | 1.4 | 16.3 | 0.6 | 34.9 | 0.4 | 4.7 | 1.5 |
| MAN | Horse | — | 29.1 | 0.9 | 17.1 | 0.5 | 32.3 | 0.3 | 5.1 | 1.4 |
| MAN | Poultry | — | 16.6 | 0.4 | 13.6 | 0.2 | 35.4 | 2.9 | 14.9 | 1.4 |
| MAN | Poultry | — | 16.8 | 0.1 | 13.5 | 0.2 | 36.3 | 0.5 | 14.2 | 1.3 |
| MAN | Pig | — | 19.6 | 1.7 | 11.6 | 0.8 | 36.8 | 0.1 | 12.4 | 1.3 |
| MAN | Cattle | Straw, after 1 month conservation | 18.8 | 0.8 | 13.6 | 0.3 | 48.5 | 2.6 | 8.5 | 1.6 |
| MAN | Turkey | — | 21.7 | 0.7 | 21.5 | 0.2 | 22.8 | 0.5 | 17.0 | 1.5 |
| MAN | Mix | — | 19.6 | 0.6 | 12.8 | 0.0 | 31.2 | 2.3 | 12.0 | 1.3 |
| MAN | Poultry | — | 20.1 | 0.2 | 14.4 | 0.1 | 23.5 | 0.6 | 28.1 | 1.4 |
| MAN | Poultry | — | 22.1 | 1.0 | 17.4 | 0.7 | 20.0 | 0.4 | 14.2 | 1.2 |
| MAN | Cattle | Straw | 13.6 | 0.1 | 8.8 | 0.1 | 52.0 | 1.9 | 5.3 | 1.9 |

**Table A2.** *Cont.*

| Family | Type | Sub Type | Cellulose | | Hemicelluloses | | Lignin | | Protein | COD |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Calculated** | **Calculated** |
| | | | **(g/100g DM)** | | **(g/100g DM)** | | **(g/100g DM)** | | **(% DM)** | **(g COD/g CxHyOz)** |
| MAN | Horse | — | 20.0 | 0.5 | 12.7 | 0.4 | 56.5 | 3.7 | 9.0 | 1.3 |
| MAN | Cattle | Straw | 29.2 | 1.4 | 16.9 | 0.2 | 30.4 | 0.3 | 7.5 | 1.3 |
| MAN | Poultry | — | 19.1 | 0.3 | 17.1 | 0.1 | 26.4 | 0.2 | 15.4 | 1.4 |
| MAN | Horse | — | 35.0 | 1.3 | 20.0 | 1.3 | 27.2 | 1.3 | 4.6 | 1.4 |
| MAN | Horse | — | 31.8 | 0.0 | 18.9 | 0.0 | 27.1 | 0.1 | 3.1 | 1.4 |
| MAN | Zoo | — | 21.9 | 0.2 | 15.2 | 0.1 | 38.6 | 1.6 | 7.8 | 1.4 |
| MAN | Cattle | Straw | 19.1 | 0.3 | 11.5 | 0.1 | 40.1 | 4.0 | 6.6 | 1.3 |
| MAN | Mix | Straw | 20.2 | 0.2 | 14.9 | 0.4 | 28.6 | 0.1 | 13.8 | 1.4 |
| MAN | Mix | Straw | 18.9 | 0.2 | 12.7 | 0.1 | 35.7 | 2.7 | 13.3 | 1.5 |
| MAN | Horse | — | 31.6 | 0.2 | 20.0 | 0.1 | 27.1 | 0.5 | 4.1 | 1.3 |
| MAN | Horse | — | 29.6 | 0.6 | 19.9 | 0.1 | 34.6 | 0.3 | 3.3 | 1.2 |
| MAN | Cattle | Straw | 28.5 | 0.2 | 15.7 | 0.1 | 36.4 | 0.0 | 12.8 | 1.3 |
| MAN | Cattle | Straw | 25.0 | 1.0 | 18.1 | 0.6 | 43.2 | 0.2 | 11.3 | 1.4 |
| MAN | Horse | — | 20.7 | 0.5 | 16.4 | 0.4 | 28.3 | 0.7 | 16.8 | 1.3 |
| CER | Maize Residues | Follicle | 49.0 | 1.2 | 10.8 | 0.5 | 12.0 | 0.0 | 8.2 | 1.3 |
| CER | Wheat | Contaminated culture | 59.3 | 1.1 | 6.0 | 0.1 | 5.5 | 0.5 | 11.3 | 1.2 |
| CER | Mix | Cereals | 50.2 | 0.6 | 7.9 | 0.3 | 14.2 | 0.0 | 9.1 | 1.3 |
| CER | Mix | Cereal dust | 29.7 | 0.4 | 21.3 | 0.3 | 21.4 | 1.2 | 6.1 | 1.3 |
| CER | Mix | Cereal residue | 33.3 | 1.7 | 14.7 | 1.2 | 16.1 | 0.1 | 22.3 | 1.4 |
| CER | Maize | Fresh residue from sweet corn | 29.5 | 1.5 | 16.1 | 1.5 | 15.4 | 0.4 | 5.1 | 1.2 |
| CER | Maize | Fresh residue from sweet corn | 25.8 | 0.4 | 18.9 | 0.2 | 16.4 | 0.0 | 6.3 | 1.2 |
| CER | Maize | Fresh residue from sweet corn | 29.5 | 0.1 | 19.0 | 0.2 | 16.2 | 0.1 | 6.3 | 1.3 |
| CER | Maize | Fresh residue from sweet corn | 29.5 | 0.2 | 20.5 | 0.0 | 12.2 | 0.1 | 5.6 | 1.3 |
| CER | Maize | Fresh residue from sweet corn | 29.0 | 0.3 | 19.9 | 0.0 | 12.9 | 0.3 | 7.6 | 1.3 |
| CER | Maize | Fresh residue from sweet corn | 27.6 | 0.4 | 16.8 | 0.6 | 16.3 | 0.2 | 4.8 | 1.3 |
| CER | Maize | Fresh residue from sweet corn | 28.4 | 0.1 | 18.9 | 0.1 | 14.0 | 0.1 | 4.8 | 1.3 |
| CER | Mix | Cereals | 29.3 | 0.9 | 10.9 | 0.3 | 18.7 | 0.4 | 22.3 | 1.5 |
| CER | Maize | Flour | 60.9 | 0.4 | 7.2 | 0.1 | 6.2 | 0.5 | 6.8 | 1.2 |
| CER | Mix | Cereals | 50.6 | 1.3 | 7.3 | 0.6 | 10.6 | 0.1 | 14.8 | 1.4 |
| CER | Mix | Silo’s lose | 51.6 | 0.7 | 10.7 | 0.5 | 18.7 | 0.5 | 4.5 | 1.2 |
| CER | Mix | Cereals | 49.3 | 1.9 | 6.8 | 0.3 | 13.3 | 0.3 | 8.9 | 1.3 |
| SLU | Cattle | — | 8.7 | 0.0 | 7.7 | 0.3 | 38.6 | 1.1 | 16.1 | 1.8 |
| SLU | Rabbit | — | 20.6 | 0.7 | 13.5 | 0.1 | 28.6 | 0.0 | 10.8 | 1.4 |

**Table A2.** *Cont.*

| **Family** | **Type** | **Sub Type** | **Cellulose** | | **Hemicelluloses** | | **Lignin** | | **Protein** | **COD** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Calculated** | **Calculated** |
| | | | **(g/100g DM)** | | **(g/100g DM)** | | **(g/100g DM)** | | **(% DM)** | **(g COD/g CxHyOz)** |
| SLU | Cattle | — | 26.4 | 0.7 | 20.0 | 0.9 | 28.8 | 0.1 | 14.0 | 1.0 |
| SLU | Duck | — | 13.2 | 0.1 | 23.5 | 1.3 | 19.1 | 0.1 | 18.6 | 1.6 |
| SLU | Cattle | — | 17.8 | 0.0 | 12.7 | 1.0 | 33.8 | 0.9 | 9.0 | 1.6 |
| LCM | Maize Residue | Cob | 29.0 | 0.6 | 26.0 | 0.4 | 19.8 | 0.1 | 0.6 | 1.2 |
| LCM | Hemp | Dust | 19.5 | 0.8 | 8.9 | 0.0 | 28.2 | 0.0 | 5.1 | 1.5 |
| LCM | Straw | Plant residues | 28.5 | 0.3 | 17.5 | 0.2 | 16.3 | 0.3 | 4.4 | 1.2 |
| LCM | Straw | — | 30.9 | 0.5 | 18.3 | 0.2 | 17.0 | 0.4 | 3.4 | 1.2 |
| LCM | Maize | Beans | 33.6 | 1.5 | 22.7 | 0.7 | 19.4 | 0.5 | 1.6 | 1.4 |
| LCM | Bagasse and Straw | — | 30.1 | 2.5 | 18.2 | 1.7 | 17.6 | 1.5 | 1.1 | 1.3 |
| LCM | Bagasse | — | 32.1 | 0.2 | 15.7 | 0.2 | 22.8 | 0.7 | 0.7 | 1.3 |
| LCM | Straw | — | 31.7 | 0.2 | 20.6 | 0.3 | 23.1 | 0.4 | 1.4 | 1.4 |
| LCM | Bagasse | — | 33.4 | 0.6 | 21.2 | 0.4 | 30.9 | 2.9 | 0.9 | 1.9 |
| LCM | Straw | Waste | 25.3 | 1.7 | 24.1 | 1.8 | 21.3 | 2.1 | 3.4 | 1.3 |
| LCM | Green waste | — | 31.9 | 0.7 | 13.8 | 0.4 | 17.9 | 1.3 | 2.0 | 1.3 |
| LCM | Straw | — | 30.5 | 0.8 | 18.5 | 0.3 | 18.8 | 0.5 | 4.2 | 1.2 |
| LCM | Hay | Meadow | 26.8 | 2.0 | 19.9 | 1.9 | 23.7 | 2.2 | 5.2 | 1.3 |
| LCM | Straw | Plant residues | 30.1 | 0.3 | 17.8 | 0.1 | 18.3 | 0.5 | 3.0 | 1.2 |
| LCM | Straw | Plant residues | 31.3 | 0.0 | 17.4 | 0.1 | 18.3 | 1.2 | 3.0 | 1.3 |
| LCM | Straw | — | 29.2 | 0.9 | 18.9 | 0.3 | 14.7 | 0.4 | 3.6 | 1.2 |
| LCM | Straw | — | 32.3 | 0.7 | 18.3 | 0.4 | 15.7 | 0.6 | 2.0 | 1.2 |
| LCM | Straw | — | 30.3 | 0.0 | 20.2 | 0.1 | 24.6 | 1.1 | 2.6 | 1.3 |
| LCM | Straw | Waste | 31.4 | 0.9 | 22.0 | 0.7 | 18.4 | 0.3 | 2.2 | 1.3 |
| LCM | Flower residue | Lavender | 20.8 | 0.7 | 12.1 | 0.5 | 30.8 | 0.1 | 6.8 | 1.4 |
| LCM | Maize | Leaf | 25.7 | 1.7 | 20.8 | 1.5 | 27.5 | 1.8 | 4.8 | 1.3 |
| LCM | Straw | Plant residues | 26.2 | 1.1 | 16.6 | 0.9 | 19.5 | 1.4 | 3.8 | 1.2 |
| LCM | Straw | Waste | 30.2 | 1.7 | 23.8 | 1.1 | 26.0 | 1.1 | 2.1 | 1.3 |
| LCM | Straw | Rapeseed waste | 24.5 | 1.5 | 11.7 | 0.8 | 23.7 | 2.0 | 8.1 | 1.3 |
| LCM | Straw | — | 29.8 | 0.2 | 19.7 | 0.3 | 20.9 | 1.1 | 1.7 | 1.2 |
| LCM | Straw | Waste | 27.8 | 2.1 | 21.5 | 1.4 | 23.7 | 1.3 | 2.3 | 1.3 |
| LCM | Green waste | — | 18.3 | 1.2 | 11.1 | 0.7 | 46.0 | 0.2 | 10.6 | 1.6 |
| LCM | Mix | Green waste | 16.8 | 1.6 | 12.5 | 1.1 | 50.2 | 4.2 | 10.7 | 1.5 |
| LCM | Green waste | — | 15.4 | 0.8 | 12.9 | 0.9 | 42.1 | 1.5 | 7.4 | 2.8 |
| LCM | Flower residue | Pomace | 17.1 | 0.8 | 7.8 | 0.0 | 17.1 | 0.6 | 13.6 | 1.3 |

**Table A2.** *Cont.*

| Family | Type | Sub Type | Cellulose | | Hemicelluloses | | Lignin | | Protein | COD |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | SD | Mean | SD | Mean | SD | Calculated | Calculated |
| | | | (g/100g DM) | | (g/100g DM) | | (g/100g DM) | | (% DM) | (g COD/g CxHyOz) |
| LCM | Straw | — | 31.5 | 0.7 | 17.0 | 0.7 | 27.9 | 2.5 | 0.6 | 1.2 |
| LCM | Flower residue | Lavender | 24.5 | 0.9 | 10.7 | 0.5 | 30.0 | 0.1 | 4.0 | 1.4 |
| LCM | Straw | Waste | 29.2 | 0.3 | 20.1 | 0.0 | 26.6 | 0.1 | 1.0 | 1.2 |

## Appendix B

**Table A3.** Literature references of BMP performed on large samples, biogas production and biochemical characterization are indicated for each families of substrates. DM: dry matter; VS: volatile solids, HCell: hemicellulose, Cell: cellulose, COD: chemical oxygen demand, Prot: proteins, and BMP: biochemical methane potential.

| Reference | N. | Sample Familly | Sample Description | DM | VS | HCell | Cell | Lignin | COD | Prot | BMP (mL CH$^4$/g VS) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [14] | 2 | Manures | Dairy and Separated liquid manure | 58–124<br>91 g/kg | 41–102<br>71 g/kg | 10% VS | 32% VS | 14% VS | 71–129<br>100 g/kg | 6% VS | 243–261<br>252 |
| | 9 | Food residue | Cheese whey, Plain pasta, Meat pasta, Used vegetable oil, Ice cream, Fresh dog food, Cola beverage, Cabbage, and Potatoes | 71–991<br>274 g/kg | 60–989<br>274 g/kg | 0–0<br>0% VS | 0–36<br>3% VS | 0–0<br>0% VS | 91–2880<br>642 g/kg | 0–19<br>10% VS | 216–649<br>390 |
| | 1 | Switchgras | Switchgrass | 930 g/kg | 905 g/kg | 42% VS | 49% VS | 8% VS | 707 g/kg | 1% VS | 122 |
| | 1 | Silage | Corn silage | 217 g/kg | 201 g/kg | | 12% VS | | - | 14% VS | 296 |
| [25] | 20 | Municipal solid wastes | Municipal solid wastes | 94–99<br>97% RM | 53–90<br>74% RM | - | - | ND–0.4<br>0.1 g/g VS | 38–279<br>145 g/g VS | 29–89<br>52 g/g VS | 87–357<br>226 |
| [26] | 95 | Grass | Meadow grass | 51 | 288 | - | - | - | - | - | 406 |
| [18] | 204 | | | 295 | 329 | | | | | | 355 |

**Table A3.** *Cont.*

| Reference | N. | Sample Familly | Sample Description | DM | VS | HCell | Cell | Lignin | COD | Prot | BMP (mL CH$^4$/g VS) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [17] | 9 | Lawn cuttings | Meadow grass, Grass mixture, White clover, and Short bluegrass | - | - | 22% VS | 28% VS | 6% VS | - | 16% VS | 298–404<br>333 |
| | 9 | Hedge cuttings | Oval-leaved privet, Ivy, Beech hedge, Chokeberry, and Ground-elder | - | - | 12% VS | 28% VS | 16% VS | - | 12% VS | 149–277<br>203 |
| | 16 | Wood cuttings | Birch tree, Plane tree, Willow, and Cypress | - | - | 12% VS | 24% VS | 24% VS | - | 10% VS | 138–245<br>177 |
| | 17 | Wild plants | Northern bluegrass, Green foxtail, Bamboo, Common reed, Tufted hair-grass, Reed canary grass, Chrysanthemum, and Dandelion | - | - | 24% VS | 38% VS | 10% VS | z | 8% VS | 106–319<br>227 |
| | 6 | Crops | Maize, Wheat straw, and Sugar beet | - | - | 30% VS | 28% VS | 4% VS | - | 8% VS | 223–479<br>404 |
| [27] | 58 | Agro-industrial wastes | Solid food processing waste and non-conformed end products | - | 4–99<br>52% DM | - | - | - | - | - | 66–845<br>396 |
| | 1 | Macroaglae | - | - | 56% DM | - | - | - | - | - | 238 |
| | 20 | Biowaste | Household organic waste | - | 3–88<br>42% DM | - | - | - | - | - | 185–845<br>370 |
| | 4 | Energy crops | Maize and switch grass | - | 89–94<br>92% DM | - | - | - | - | - | 211–370<br>264 |
| | 11 | Fatty waste | Industrial sludge digester with fatty feedstock | - | 0–29<br>13% DM | - | - | - | - | - | 53–1321<br>475 |
| | 14 | Meat waste | Slaughterhouse waste or stale meat | - | 23–96<br>70% DM | - | - | - | - | - | 172–594<br>475 |
| | 2 | Co-digestion mix | | - | 83% DM | - | - | - | - | - | 185 |
| | 66 | Municipal solid wastes | Fresh wastes collected from different localisation and after different treatment | - | 15–85<br>60% DM | - | - | - | - | - | 26–423<br>211 |

**Table A3.** *Cont.*

| Reference | N. | Sample Familly | Sample Description | DM | VS | HCell | Cell | Lignin | COD | Prot | BMP (mL $\text{CH}^4$/g VS) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 42 | Plant and Vegetable | Wheat and barley residues, Potatoes, Tomatoes, etc. | - | 42–95<br>81% DM | - | - | - | - | - | 0–449<br>264 |
| | 18 | Agro-industrial sludges | Sludges produced from agro-industrial WWTP | - | 2–80<br>18% DM | - | - | - | - | - | 0–687<br>317 |
| | 30 | Sewage sludge WWTP | Different WWTP at different process steps (pre-treated or not) | - | 11–84<br>66% DM | - | - | - | - | - | 13–343<br>172 |
| | 31 | Stabilised municipal solid waste | Landfill drillings | - | 14–66<br>40% DM | - | - | - | - | - | 0–264<br>132 |
| [20] | 14 | Leaf | Reed canary grass | - | - | 22–36<br>31% DM | 16–29<br>26% DM | 1–5<br>3% DM | - | - | 321–388<br>352 |
| | | Steam | Reed canary grass | - | - | 24–34<br>30% DM | 21–41<br>35% DM | 1–10<br>7% DM | - | - | 283–417<br>344 |
| [24] | 3 | Manures | Chicken, Dairy, and Swine manures | 26–39<br>32% FM | 20–29<br>23% FM | 15–28<br>22% DM | 11–20<br>17% DM | 2–17<br>8% DM | - | 13–20<br>17% DM | 51–322<br>223 |
| | 3 | Crops straws | Corn stover, Wheat straw, and Rice straw | 85–93<br>89% FM | 77–82<br>79% FM | 25–30<br>27% DM | 41–42<br>42% DM | 8–11<br>10% DM | - | 3–6<br>4% DM | 241–281<br>256 |
| | 5 | Food and green wastes | Kitchen waste, Fruit and vegetable, Used animal/vegetable oil, and Yard waste | 4–100<br>60% FM | 3–100<br>57% FM | 0–20<br>7% DM | 0–21<br>10% DM | 0–11<br>5% DM | - | 0–21<br>9% DM | 183–811<br>531 |
| | 2 | Processing organic wastes | Vinegar residue and Rice husk | 90–92<br>91% FM | 74–85<br>80% FM | 18–33<br>26% DM | 23–41<br>32% DM | 12–20<br>16% DM | - | 3–12<br>7% DM | 49–253<br>151 |
| | 1 | Energy crops | Switchgrass | 91% FM | 87% FM | 32% DM | 43% DM | 11% DM | - | 3% DM | 246 |
| | 2 | Lignocellulosic biomass | Chenopodium album leaf, seed, and stalk | 84–86<br>85% FM | 78–83<br>81% FM | 17–19<br>18% DM | 20–39<br>30% DM | 8–16<br>12% DM | - | 3–17<br>10% DM | 171–262<br>217 |
| [28] | 88 | All | | - | 87–96<br>92% DM | | 9–76<br>57% DM | | - | - | 104–502<br>251 |

**Table A3.** *Cont.*

| Reference | N. | Sample Familly | Sample Description | DM | VS | HCell | Cell | Lignin | COD | Prot | BMP (mL CH$^4$/g VS) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [16] | 18 | Miscanthus | Miscanthus giganteus | - | - | 25% DM | 44% DM | 9% DM | - | 4% DM | 263 |
| | 16 | Switchgrass | | - | - | 33% DM | 40% DM | 7% DM | - | 4% DM | 213 |
| | 36 | Spelt straw | | - | - | 31% DM | 44% DM | 7% DM | - | 2% DM | 275 |
| | 37 | Fiber sorghum | Winter and Autumn | - | - | 22–25<br>24% DM | 33–42<br>37% DM | 5–7<br>6% DM | - | 4–7<br>5% DM | 363–438<br>400 |
| | 369 | Tall Fescue | Spring, Summer, and Autumn | - | - | 22–25<br>24% DM | 25–29<br>27% DM | 4–4<br>4% DM | - | 9–11<br>10% DM | 400–425<br>408 |
| | 21 | Immature rye | | - | - | 18% DM | 22% DM | 2% DM | - | 9% DM | 525 |
| | 73 | Fiber corn | Winter and Autumn | - | - | 2–4<br>3% DM | 20–20<br>20% DM | 18–18<br>18% DM | - | 5–7<br>6% DM | 313–400<br>356 |
| [29] | 23 | Anaerobic sludges | Effluent from anaerobic digesters | - | - | - | - | - | - | - | 32–214<br>73 |
| | 30 | Standard compounds | Cellulose, Starch, and Gelatine | - | - | - | - | - | - | - | 289–407<br>361 |
| | 50 | Household wastes | Fruit and vegetable waste, Milk waste, Meat waste, and Co-digestion mixtures | - | - | - | - | - | - | - | 214–900<br>461 |
| | 10 | Agriculture wastes | Wheat straw, Bamboo waste, and Banana stem | - | - | - | - | - | - | - | 139–300<br>224 |
| | 19 | Sewage sludges | Primary and secondary Sludge and Co-digestion mixtures | - | - | - | - | - | - | - | 171–429<br>353 |
| | 6 | Lipid rich wastes | Butter and Oil wastes | - | - | - | - | - | - | - | 793–943<br>891 |
| [5] | 6 | Cereal crops | Barley, Wheat, Triticale, and Oats | 54–69<br>62% FM | 49–67<br>58% FM | - | - | - | - | - | 281–366<br>336 |
| | 3 | Oil seed rapes | Macerated, Whole crop, and Not macerated | 88–93<br>91% FM | 85–89<br>87% FM | - | - | - | - | - | 215–646<br>393 |
| | 7 | Root crops | Potatoes, Turnips, Sugar beet, Energy beet, and Fodder beet | 11–26<br>19% FM | 10–25<br>18% FM | - | - | - | - | - | 306–399<br>349 |
| | 5 | Grass silages | Grass silage and Fresh grass | 12–29<br>19% FM | 11–27<br>18% FM | - | - | - | - | - | 368–400<br>385 |
| | 2 | Baled silages | - | 17–17<br>17% FM | 15–16<br>15% FM | - | - | - | - | - | 428–433<br>431 |

**Table A3.** *Cont.*

| Reference | N. | Sample Familly | Sample Description | DM | VS | HCell | Cell | Lignin | COD | Prot | BMP (mL $CH^4$/g VS) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 8 | Other grass substrates | Silage, Hay, Savazi grass, Silage effluent, Grass digestate, Fresh maize, and Maize silage | 6–87<br>29% FM | 3–82<br>27% FM | - | - | - | - | - | 127–394<br>324 |
| | 7 | Dairy slurries | - | 6–9<br>7% FM | 4–7<br>6% FM | - | - | - | - | - | 136–239<br>201 |
| | 4 | Other agricultural wastes | Beef slurry, Pig slurry, Poultry manure, and Farm yard manure | 5–51<br>21% FM | 4–30<br>14% FM | - | - | - | - | - | 99–311<br>194 |
| | 4 | Milk processing wastes | Sludges with or without dissolved air floatation | 4–16<br>9% FM | 3–9<br>7% FM | - | - | - | - | - | 189–787<br>473 |
| | 4 | Abattoir wastes | Mix, paunch content, and Sludges | 13–20<br>17% FM | 11–18<br>15% FM | - | - | - | - | - | 166–404<br>286 |
| | 7 | Miscellaneous wastes | Bakery waste, Brewing stillage, Grocery waste, Fish offal mix, Bread waste, Park and grass waste, and WWTP | 9–66<br>32% FM | 7–64<br>29% FM | - | - | - | - | - | 247–592<br>396 |
| | 10 | Domestic and commercial food wastes | Rural and urban food waste, Food wastes from canteens and restaurants, and Centralised collection centre combining the two types or not | 22–95<br>37% FM | 19–88<br>32% FM | - | - | - | - | - | 274–535<br>329 |
| | 3 | Alternative wastes | Recycled paper, Used cooking oil, and Grease trap wastes | 27–100<br>72% FM | 26–99<br>68% FM | - | - | - | - | - | 254–805<br>434 |
| | 12 | Seaweeds | 9 brown & 3 green Seaweeds | 13–78<br>23% FM | 8–46<br>15% FM | - | - | - | - | - | 101–341<br>213 |
| [19] | 24 | Main and secondary crops | Sugar beet, Barley/ryegrass, Maize, Triticale, Marrow stem kale, Rye/triticale, Potatoes, Oat/forage Pea/false flax, Rye, Sundangrass, Forage sorghum, Rye/fodder vetch, Barley/turnip rape, Oat, Amaranth, Quinoa, Rapeseed, Sunflower, Forage pea, and Buckwheat | 9–59<br>33% FM | 81–97<br>92% DM | 2–25<br>15% DM | 3–37<br>27% DM | 1–13<br>6% DM | - | 4–19<br>9% DM | 210–399<br>294 |

**Table A3.** *Cont.*

| Reference | N. | Sample Familly | Sample Description | DM | VS | HCell | Cell | Lignin | COD | Prot | BMP (mL $CH^4$/g VS) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [30] | 10 | Catch crops | Triticale, Barley, Rye, Landsberger mix, Sudengrass hybrid, Forage sorgum, Ryegrass, Phacelia, Fodder radish, and Buckwheat/phacelia | 9–58<br>24% FM | 73–96<br>90% DM | 0–24<br>17% DM | 24–34<br>30% DM | 2–9<br>5% DM | - | 5–26<br>11% DM | 235–376<br>311 |
| | 4 | Annual grass and legume mix | Ryegrass, Clover, Alfalfa clover, and Alfalfa | 15–48<br>28% FM | 85–93<br>90% DM | 11–18<br>14% DM | 26–29<br>28% DM | 4–7<br>5% DM | - | 7–20<br>14% DM | 240–388<br>307 |
| | 5 | Perennial crops | Tall wheatgrass, Countru mallow, Jerusalem artichoke, Miscanthus, and Cup plant | 14–40<br>28% FM | 85–97<br>90% DM | 5–24<br>16% DM | 28–42<br>33% DM | 7–13<br>10% DM | - | 4–15<br>9% DM | 179–259<br>228 |
| | 58 | Solid manure | | 2–99% FM | 1–92% DM | - | - | - | - | - | 129–366<br>225 |
| | 7 | Animal slurries | | | | - | - | - | - | - | 225–551<br>293 |
| | 3 | Slaughterhouse waste | | | | - | - | - | - | - | 186–664<br>349 |
| | 16 | Mix of AD feedstock | | | | - | - | - | - | - | 90–253<br>101 |
| | 6 | AD digestats | | | | - | - | - | - | - | 214–405<br>304 |
| | 36 | Grass and intermediate crops | | | | - | - | - | - | - | 191–444<br>304 |
| | 24 | Cereals and crop residues | | | | - | - | - | - | - | 191–388<br>304 |
| | 26 | Silages | | | | - | - | - | - | - | 186–495<br>338 |

**Table A3.** *Cont.*

| Reference | N. | Sample Familly | Sample Description | DM | VS | HCell | Cell | Lignin | COD | Prot | BMP (mL $CH^4$/g VS) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [30] | 38 | Lignocellulosic plants | | | | - | - | - | - | - | 62–326<br>270 |
| | 15 | Grape marcs | | | | - | - | - | - | - | 79–219<br>129 |
| | 3 | Algae | | | | - | - | - | - | - | 146–169<br>165 |
| | 25 | Food wastes and biowastes | | | | - | - | - | - | - | 96–518<br>338 |
| | 10 | Sludges | | | | - | - | - | - | - | 56–776<br>259 |
| | 3 | Effluents | | | | - | - | - | - | - | 225–281<br>276 |
| | 3 | Fat and lipid wastes | | | | - | - | - | - | - | 596–878<br>630 |
| | 2 | Products and wastes from meat | | | | - | - | - | - | - | 203–388<br>293 |
| | 2 | Organic fraction of municipal waste | | | | - | - | - | - | - | 281 |
| [21] | 41 | Energy crops | Barley, Clover, Cup plant, Grassland, Maize, Millet, Potatoes, Rye, Sugar beet, Sunflower, and Triticale | 88–94<br>91% FM | 79–89<br>85% FM | 3–28<br>18% DM | 5–39<br>27% DM | 0–11<br>4% DM | - | 4–20<br>9% DM | 177–401<br>311 |
| [22] | 43 | Grasses | Lolium perenne, Dactylis glomerata, Poa pratensis, and Fescuta pratensis | 87–94<br>91% FM | 78–88<br>84% FM | 21–32<br>26% DM | 20–36<br>29% DM | 2–7<br>4% DM | - | 6–20<br>11% DM | *314–422*<br>*353* |
| | 18 | Legumes | Trifolium pratense and Repens | 88–93<br>90% FM | 80–85<br>82% FM | 3–22<br>11% DM | 16–33<br>25% DM | 5–9<br>7% DM | - | 13–29<br>21% DM | *265–346*<br>*301* |

**Table A3.** *Cont.*

| Reference | N. | Sample Familly | Sample Description | DM | VS | HCell | Cell | Lignin | COD | Prot | BMP (mL CH$^4$/g VS) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [13] | 2 | Biowaste | Banana peel waste, Tomato waste, and | 11% FM | 83% DM | - | - | - | 2 g O2/g VS | - | 329 |
| | 1 | Effluent | Winery wastewater | 3% FM | 65% DM | - | - | - | 3 g O2/g VS | - | 251 |
| | 10 | Plants | | ? | ? | ? | ? | ? | ? | ? | 111–379<br>229 |
| | 21 | Vegetables | | ? | ? | ? | ? | ? | ? | ? | 186–443<br>314 |
| | 24 | Fruits | | ? | ? | ? | ? | ? | ? | ? | 185–529<br>314 |
| | 7 | Cereals | | ? | ? | ? | ? | ? | ? | ? | 261–325<br>293 |
| | 12 | Manures | | ? | ? | ? | ? | ? | ? | ? | 154–325<br>211 |
| | 17 | Diet | | ? | ? | ? | ? | ? | ? | ? | 250–775<br>432 |
| | 10 | Sludges | | ? | ? | ? | ? | ? | ? | ? | 164–711<br>411 |
| | 4 | Beverage wastewaters | | ? | ? | ? | ? | ? | ? | ? | 250–593<br>411 |
| | 18 | Organic fraction of municipal solid wastes | | ? | ? | ? | ? | ? | ? | ? | 175–571<br>464 |
| | 8 | Other | | ? | ? | ? | ? | ? | ? | ? | 207–443<br>379 |
| [23] | 20 | Sludges | 10 primary and 10 bioglogical Sludges | 5–46<br>21% FM | 4–33<br>15% FM | - | - | - | 1–2<br>2% VS | 0–60<br>28 mg BSA/g VS | 58–318<br>181 |

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