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Review of inventory data for the biological treatment of sewage sludge

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Abstract

The biological treatment of municipal sewage sludge in terms of anaerobic digestion and composting was reviewed with the purpose of establishing inventory data addressing all inputs and outputs of sludge treatment. We identified 193 scientific papers, 87 of which contained inventory data resulting in 64 datasets on anaerobic digestion and 35 datasets on composting. In anaerobic digestion, biogas production varied significantly (up to a factor of four) depending on the sludge. A useful correlation was identified between the amount of methane produced and the degradation of volatile solids. According to statistical tests, no significant differences were found in biogas production for mesophilic and thermophilic digesters. In addition, methane content varied significantly and very few data were available on digestate composition nor energy consumption and recovery. In composting, accurate estimates relating to the degradation of the sewage sludge could not be made, since organic bulking materials added to the process for practical reasons were part of the final composted product. Data on emissions into the air (CH_4, NH_3 and N_2O) are currently scarce, which points to the need for more published data. The inventory data evaluated herein are useful in feasibility assessment of biological treatment of sewage sludge, for technology comparison, for examples in LCA studies, and as a basis for evaluating the performance of a specific biological sludge treatment plant. However, much of the data reviewed was from laboratory and pilot-scale studies and there is a need for more complete datasets on the performance of full-scale technologies, in order to establish full inventories and identify differences in technology and operational conditions.

Keywords: Sewage sludge; biological treatment; anaerobic digestion; composting; inventory data

1. Introduction

The biological treatment of municipal sewage sludge is common in rural as well as urban areas. Biological treatment may occur in the absence of oxygen, as in the case of anaerobic digestion, or in the presence of oxygen, as in composting. Sometimes, the processes are combined, whereby, after digestion, the digested sludge is composted.

The anaerobic digestion of sewage sludge provides stabilisation and allows for the recovery of energy and nutrients from the sludge. It is estimated that there are more than 132,000 anaerobic digesters in the world, more than 1300 of which treat sewage sludge (IEA Bioenergy, 2001; World Biogas Association, 2019). Several technologies are available, and the key technological factors are process temperature, dry or wet processes, mixing, retention time, the use of additives and the capture of generated gas. Lavergne et al. (2018) and Gebreeyessus and Jenicek (2016) provided overviews of common digester technologies for sewage sludge treatment.

Composting of sewage sludge provides stabilisation and allows recovery of nutrients and organic matter (Wang et al., 2021). We found no statistics about the numbers of composting plants dealing with sewage sludge. Several technologies are available, and the key technological factors are the use of bulking materials, to improve accessibility to oxygen, and the way of providing air supply either by aeration or by turning (Golbaz et al., 2021; Liu et al., 2020; Ma, 2020; Naserian et al., 2021; Wang et al., 2020). In some cases, composting takes place in the open, while in other cases it takes place in a reactor or a building that controls air ventilation (Han et al., 2018b; Pognani et al., 2011; Shen et al., 2020; Zheng et al., 2018). Benedict et al. (1986) described a number of different sewage sludge composting technologies.

Since the information about inventory data describing the performance of biological treatment technologies for sewage sludge is not accessible in existing studies, we performed a literature review on input and output data describing the performance of anaerobic digestion and the composting of municipal sewage sludge, the latter for both raw and digested sewage sludge. Vermiculture (Guzman et al., 2020; Włóka et al., 2020) and reed beds (Brix, 2017; Rozkosny et al., 2020) are also biological treatment options for sewage sludge, but they are not included in this study because of their limited use worldwide. Co-treatment of municipal sewage sludge with other sludge types or with manure is not covered, since general data on sewage sludge rarely can be extracted from co-treatment studies. Inventory data are useful in feasibility assessment of introducing biological treatment, for technology comparisons and as a comparative basis for evaluating the performance of a specific biological sewage sludge treatment plant. Inventory data also act as the basis for performing a life cycle assessment (LCA). The purpose of this paper is to summarise and analyse inventory data describing the anaerobic digestion and composting of municipal sewage sludge in the scientific literature. This allows us to identify the gaps in inventory data on these biological treatments of sewage sludge.

2. Materials and methods

We accessed the database of Web of Science^{TM} for the period 2003 – 2021 searching for papers related to sewage sludge digestion and composting. The keywords used for literature searching are listed in the Supplementary Information A1. We identified 193 papers, 87 of which contained inventory data, 64 datasets on sewage sludge digestion and 35 datasets on sewage sludge composting. The 87 papers are listed in Supplementary Information A2.

The following paragraphs describe the data assessment and define the technologies, including the inventory parameters reviewed.

2.1 Data assessment

All of the collected data were compiled and grouped in Excel according to sludge type and biotreatment technology, as defined in the following sections.

The data were checked for an adequate description of technological features and for their plausibility by comparing the values of each parameter within its own group and with other relevant parameters. Mass balances were assessed (See Supplementary Information A1) and datasets showing large discrepancies were excluded. Not all datasets contained all relevant parameters, but as long as the reported data showed internal consistency, they were included in the assessment.

Intervals, average values, standard deviations and numbers of datasets were specified for all inventory parameters. Technically meaningful correlations and regressions between data were identified and, where statistically significant, regression equations and analyses of variance were established. The software Origin® was used for the statistical analysis and presentation. In some histograms we show frequency distribution where statistically relevant. The probability density functions and the test statistics are described in Supplementary Information A1.

Since the data reported and assessed herein are of different scales, ranging from laboratory-scale and pilot-scale to full-scale, it is important to be aware of the origins and limitations of the reviewed information. Data from full-scale plants report on how the technology is actually performing, although it does not necessarily represent optimal conditions. Data from pilot-scale and laboratory-scale experimental set-ups may represent a range of investigated operational conditions in order to define the best conditions to be used in a prospective full-scale operation. We report all the data we have identified as consistent, albeit some of them may not represent optimal conditions or become implemented in full-scale cases. In addition, the scale may also affect the performance of a reactor, due to differences in mixing, heat distribution, etc. (Lafratta et al., 2021). We mark the data presented in this paper according to scale, where meaningful and feasible.

2.2 Anaerobic digestion

The digestion of sewage sludge is performed under anaerobic conditions at elevated temperatures for extended time periods during mixing. 64 relevant studies (n=64) on anaerobic digestion of sewage sludge were involved in this review. The technology is characterised by:

a) The solid content of sludge in the reactor. The process is either dry digestion, where sewage sludge is present at a high solid content (15 – 25% total solids, TS) (An et al., 2017; Li et al., 2018; Wang et al., 2018a), or a wet digestion, where sewage sludge is present at a low solid content (3 – 10% TS) (Odirile et al., 2021; Soda et al., 2010; Wang and Su, 2020).

b) Hydraulic retention time, which typically varies between 10 and 30 days.

c) Temperature, which is typically either mesophilic (35 – 38°C) or thermophilic (50 – 57°C).

These factors influence the amount of biogas produced, although operational conditions may also affect process efficiency. If the retention time in the reactor is relatively short, post-storage aligned with residual biogas collection may be used.

Predicting how much CH_4 can be generated is crucial in the early stages of considering introducing anaerobic digestion of sewage sludge. Several methods are available for estimating the amount of CH_4 that can be microbiologically produced from an organic substrate, including sewage sludge, under optimal conditions in the laboratory, for example the Biochemical Methane Potential measurement (Mirmasoumi et al., 2018; Nghiem et al., 2017; Shao et al., 2013). Other methods have been developed that correlate surface-related measurements on substrates to methane potentials measured in the lab (Cruz Viggi et al., 2014; Rotaru et al., 2014; Sheng et al., 2010; Ye et al., 2014). Furthermore, advanced biochemical models predict methane production in specific technological conditions, based on a range of specified parameters (Otuzalti and Perendeci, 2018, 2019). In the detailed planning phase, as well as in the design phase, advanced models are useful, but early in the planning process, when specific technological decisions are not yet made, simple estimates are required on how much CH_4 can be expected in general. Data from actual plants are crucial in this regard.

Digester outputs are biogas and digestate, with the latter in some cases split into a solid and a liquid fraction, each of which is treated separately. The biogas is often combusted on-site to produce electricity and heat the digester. Biogas may also be upgraded to natural gas quality. The use of the biogas and digestate is not considered in this review.

The main consumables are electricity and heat to run the plant. In some cases, micronutrients as well as anti-foaming agents are added.

The inventory parameters used to characterise the performance of sewage sludge digestion are as follows:

a) Biogas or methane generation per unit of input, which may be total solids (TS) or volatile solids (VS). This reflects how much gas can be obtained and how stabilised the sewage sludge becomes after digestion: the more biogas generated, the more stabilised the sewage sludge.
b) Methane content of the biogas, which determines its calorific content and subsequent use.
c) Digestate composition, which determines its further handling.
d) Energy budget, including the consumption and recovery of electricity, heat and fuel, which is crucial for quantifying environmental impacts.

2.3 Composting

Composting of sewage sludge is performed under aerobic conditions at elevated temperatures for an extended time. 35 relevant studies (n=35) on composting of sewage sludge were involved in this review. The technology is characterised by:

a) Bulking material: solid materials are added to the sewage sludge in order to provide a structure to allow air to enter. These bulking materials may be selected materials from stabilised compost, garden waste, wood chips, straw or other agricultural or horticultural waste products, as well as non-organic items, which can be removed at the end of the composting process, for example shredded car tires. The bulking material may also serve in adjusting the C/N ratio of the mix, in order to ensure good conditions for microbial activity. The amount of added bulking material varies significantly, potentially depending on technical choice, its availability or if it in itself constitutes a waste management problem that needs to be solved, as may be the case when shredded woody garden waste is used as bulking material.
b) Aeration methods: Forced aeration through static stacks or frequent mechanical turning of stacks. Combinations of forced aeration and mechanical turning are also found.
c) Retention time: In full-scale plants, the retention time is typically 20 – 55 days, including active composting and final maturation. In pilot- and laboratory-scale experiments, retention time may be even longer.
d) The level of confinement after mixing sewage sludge and bulking material: sewage sludge composting may take place in the open air in windrows, which are aerated or mechanically turned, or in confined spaces, such as closed reactors or vented buildings. The more the system is confined, the better is the possibility of controlling aeration, temperature and moisture content during the process, as well as the moisture content of the final compost product. The ventilation air may be treated in a filter prior to its release.

Technologically, two different approaches for sewage sludge composting have been considered in this review, each of them with many variations:

a) Reactor composting (RC) ($n = 8$): Composting takes place as a batch in a closed reactor with an air flow. The air input is 0.4 – 2.5 L / (min·kg TS), often supplied at intervals, for example 10 minutes every hour. The temperature may reach 64 °C for 10 – 20 days. Some reactors provide mechanical mixing. Afterwards, the compost is matured in windrows, typically for 5 – 10 days.

b) Windrow composting (WC) (n = 27): Composting takes place for 25 – 55 days in the open in 1 – 3 m high piles. The windrows are turned mechanically, and in some cases they are also mechanically aerated. Turning takes place every 3 – 7 days to ensure that all of the material becomes exposed to high temperatures.

The output from composting is compost. The final step in the process may include screening to remove foreign items or bulking materials, which can be potentially recycled back into the composting process. The former is expected to be a very small fraction and is not addressed further herein. The compost can be used in soil manufacturing, landscaping or as a soil amendment. Details relating to compost use are not included in this review.

The main energy and materials consumed are electricity and fuels to run the plant; in particular, blowers and turning machines use energy.

Inventory parameters characterising the performance of sewage sludge composting are as follows:

a) Use of bulking material (amount and quality).

b) Compost composition, which determines its further handling. Key parameters are nutrients and contaminant content. Except for some organic contaminants, most contaminants are stable during composting (Rodríguez et al., 2012; Wang et al., 2019; Zorpas and Loisidou, 2008), and so levels in the compost are primarily controlled by the composition of the sewage sludge. Contaminant levels in compost vary greatly and are not included in this review. In many countries, there are legal limits on contaminants in compost added to soil (Brinton, 2000). Nutrient contents are reviewed, as they may represent fertiliser values.

c) The composition of air emissions from the composing process or any filters installed. Potentially concerned emissions are methane, ammonia and dinitrogen oxide. Odours may be an issue locally, but they are not included in this review.

d) Consumed energy and materials including electricity and fuels.

3. Results and discussion

3.1 Anaerobic digestion

The results for anaerobic digestion are presented in the following paragraphs in terms of the amount of biogas, biogas composition, digestate and energy budgets. Inventory data for dry digesters were available only from laboratory-scale experiments and are not included in the data presented below.

3.1.1 Anaerobic digestion: Biogas amount

Figure 1 presents the amount of biogas per kg TS input as a function of the volatile solid content (VS) of sludge solids. The data are marked according to their scale (laboratory-scale, pilot-scale, full-scale) as well as digester temperature (mesophilic, thermophilic, not specified). There are significant variations, but a clear tendency exists for higher amounts of biogas in the presence of higher VS content. There is no clear effect in terms of the scale of the reported data or digester temperature.

The regression (number of data, n = 44) forced through origo is good (r^2 = 0.95), as represented by Eq. (1):

$$Biogas\ generation\ (m^3/\ kg\ TS) =\ 0.0043\ \times\ VS\ input\ (\%\ of\ TS) \tag{1}$$

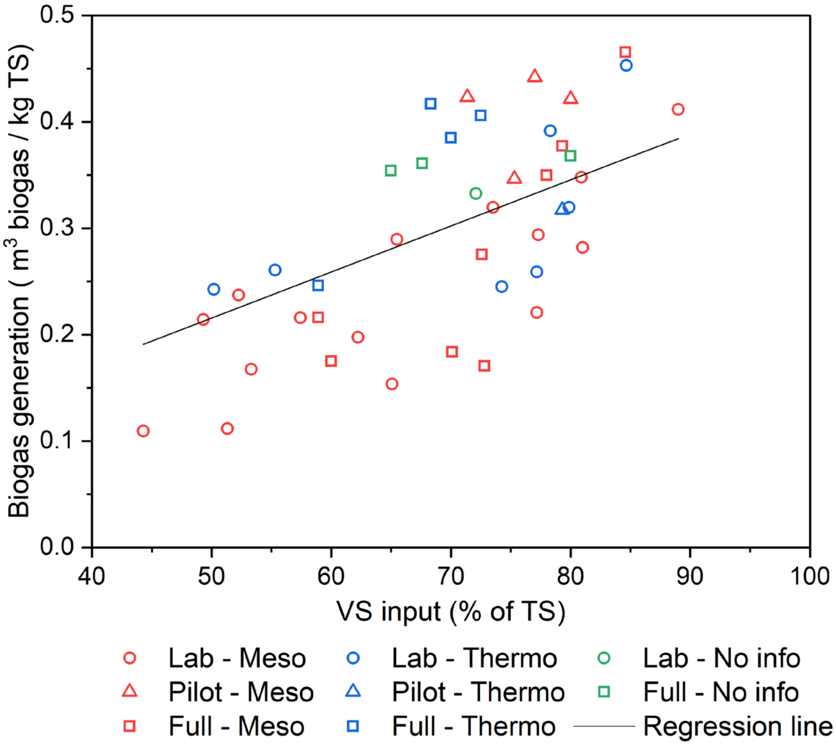

Fig. 1. Anaerobic digestion of sewage sludge: Amount of biogas per kg TS (m^3 biogas/kg TS) as a function of the VS content of the solids (% of TS)

Some datasets report the degree of degradation of the VS and specify gas composition, thereby making it possible to present the amount of CH_4 generated as a function of the degree of VS degradation. This is shown in Figure 2.

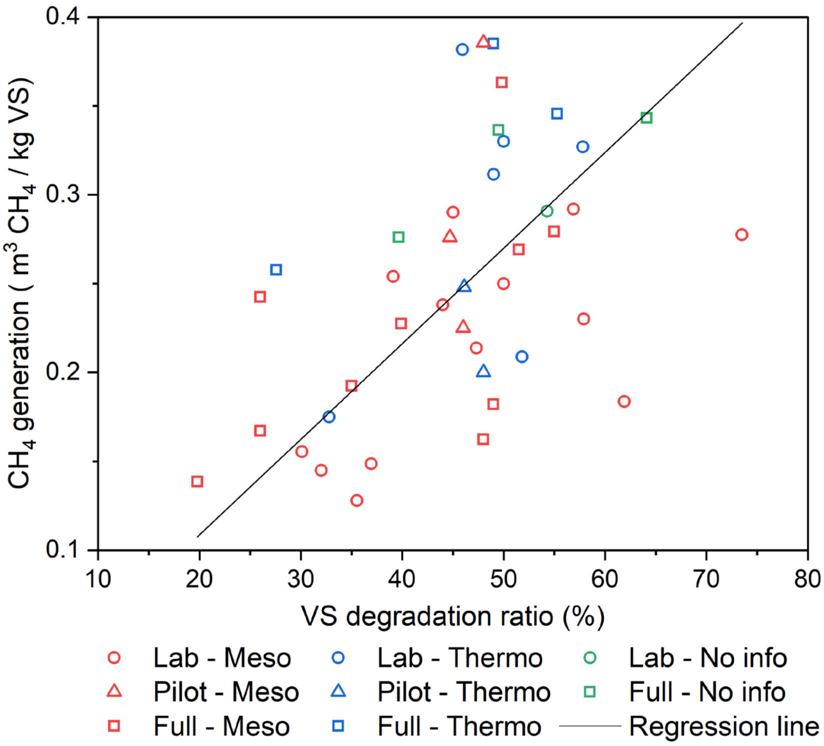

Fig. 2. Anaerobic digestion of sewage sludge: Amount of CH_4 (m^3 CH_4/kg VS) as a function of the degradation of VS (%VS degraded).

The regression (n= 41) forced through origo is good ($r^2 = 0.97$), as represented by Eq. (2):

$$CH_4\ generation\ (\mathrm{m^3\ CH_4/kg\ VS}) = 0.0054\ \times VS\ degradation\ ratio\ (\%) \qquad (2)$$

The reported data on the VS degradation (Figure 2, x-axis) vary from 20% to 73% VS degradation. Average VS degradation is 46% ± 11% (average ± standard deviation, n = 52). A low value in this regard would suggest that the anaerobic digester does not perform well. Note that only three values were above 60% VS degradation. Considering values above 45% VS degradation, the thermophilic digesters showed average methane production levels of 0.304 ± 0.076 m^3 CH_4/kg VS (n = 9), while the mesophilic digesters showed 0.257 ± 0.060 m^3 CH_4/kg VS (n = 14); however, this difference is not statistically significant according to the reported data ($p = 0.115$). Hydraulic retention time may also affect the degree of degradation, suggesting more degradation over longer retention times. Unfortunately, information about actual retention times was incomplete and we could not determine the importance of this factor from the reported data.

Since CH_4 generation is the most important parameter in terms of energy recovery, environmental aspects and economy, the standardized Biochemical Methane Potential (BMP) measurement is a common way of directly measuring a sample in the laboratory (Mirmasoumi et al., 2018; Nghiem et al., 2017; Shao et al., 2013), in order to make a first estimate of the amount of methane that could be generated. However, only a few of the reviewed papers on digester performance presented data on BMP values, and thus it was not possible to assess how this commonly used laboratory test would fit with data from the digesters. Chang et al. (2022) reviewed and summarised BMP values of sewage sludge from 58 relevant studies, showing an average of 0.25 ± 0.11 m^3 CH_4/kg VS. If this general average were linked to Figure 2 by assuming all VS is degradable, estimated methane generation would be less than observed in this review. This may in turn suggest that not all of the VS in sewage sludge is degradable during anaerobic digestion. Based on the data reviewed, the BMP test seems less useful for estimating how much CH_4 can be obtained practically via the digestion of sewage sludge.

3.1.2 Anaerobic digestion: Biogas composition

The main components of biogas from sewage sludge digestion are CH_4 and CO_2. Biogas also contains traces of other gases; for example, Dohanyos et al. (2004), Spinosa et al. (2011) and Wu et al. (2018) reported H_2S concentrations of 14 – 140 ppm, Alibardi et al. (2017) reported H_2 concentrations of 80 – 140 ppm, while Akgul et al. (2017) addressed the odour composition of biogas.

Focusing on methane content, Figure 3 shows the percentage of CH_4 in biogas as a function of methane generation. It shows that there is no relation between the methane generation and the percentage of methane in the biogas. We found no statistically significant difference in the percentage of CH_4 between thermophilic digesters (65.9 ± 5.2 %, n = 13) and mesophilic digesters (63.2 ± 4.5 %, n = 24).

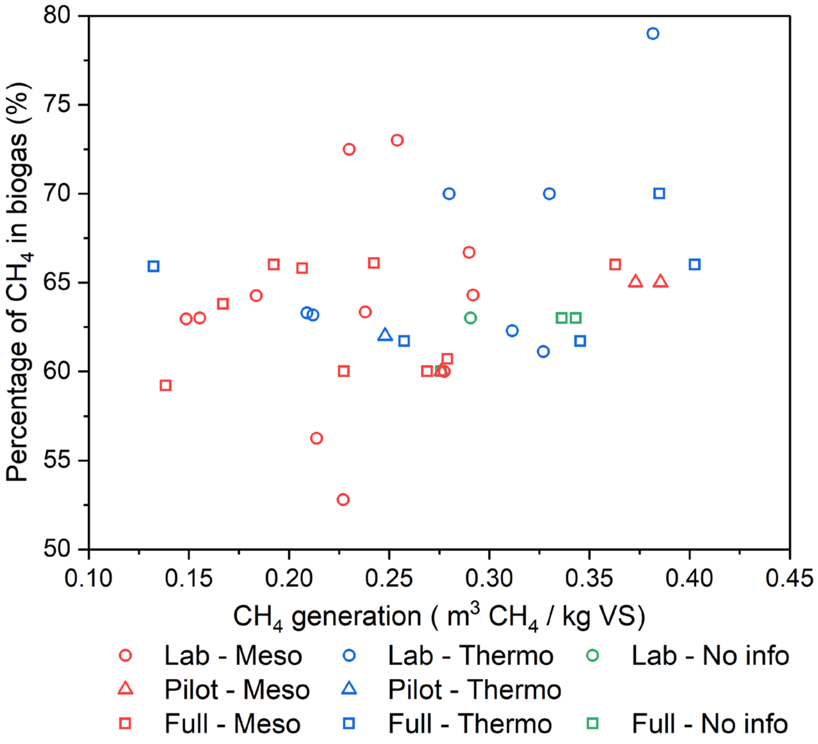

Fig. 3. Anaerobic digestion of sewage sludge: Percentage of CH_4 in biogas as a function of CH_4 generation (m^3 CH_4/kg VS)

The distribution of the reported methane content is shown in Figure 4, The variation is large (52 – 79% CH_4), with an average CH_4 content of 64 ± 5 % (n = 41). The concentration of CH_4 in the gas is higher than when generated initially during the microbial fermentation process, because some of the CO_2 dissolves into the liquid fraction.

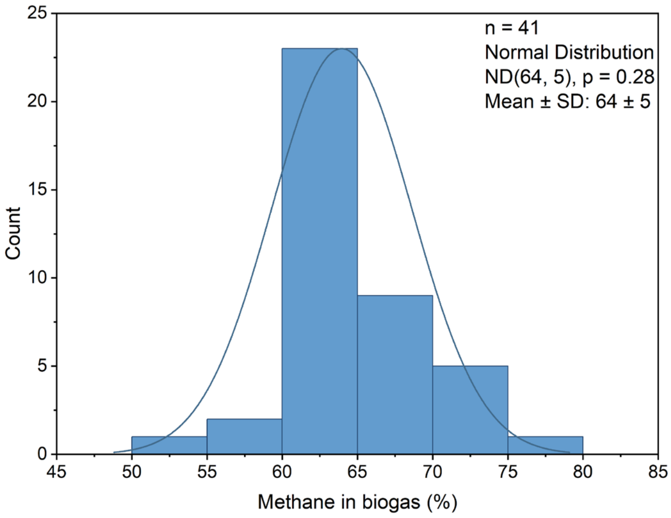

Fig. 4. Anaerobic digestion of sewage sludge: Distribution of CH_4 content in biogas from sewage sludge.

3.1.3 Anaerobic digestion: Digestate

Only a few of the reviewed papers contained data on the composition of digestate, i.e. effluent from the digester. Digester effluent is dilute, its average total solid content is 4.0 ± 2.8 % of wet weight (n = 35) and it is usually dewatered before further handling.

Digestate dewatering via a filter press or centrifugation technology yields a final TS content for the solid digestate of 30.3 ± 9.4 %TS (n = 10) with an average use of polymers of 12.9 ± 6.1 g/kg TS obtained (n = 4) and the consumption of 0.26 ± 0.13 kWh electricity/ kg TS input (n = 3). The fate of the VS in the digestate was addressed in only two cases: Houdkova et al. (2008) and Turek et al. (2018) reported that 99.5% and 91.3%, respectively, of VS were found in the solid digestate fraction, while the remaining part was in the liquid digestate fraction. A few reports provide actual data on liquid digestate composition (Ciaciuch et al., 2017; Hermassi et al., 2017; Shao et al., 2013): COD 2019 – 14663 mg/L, BOD 220 – 550 mg/L, TOC 200 – 3168 mg/L, TN 700 – 2190 mg/L and TP 63 – 224 mg/L, respectively. However, since data on volume of digestate were few, we could not estimate transfer coefficients expressing the distribution of the content of the digestate into solid and liquid fractions.

3.1.4 Anaerobic digestion: Energy

Energy consumption and the recovery of full-scale digesters are shown in Figure 5, including both electricity and heat with a unified unit (kWh). Energy loss is calculated, where the data allowed us to do so, as the difference between energy content in the generated biogas and the sum of recovered electricity and heat. Energy is used for the mechanical operation of the facilities and, eventually, for heating the reactor, while electricity and heat are recovered from the combustion of biogas. Recovered heat may be used to heat the reactor. On average, in kWh/kg wet input, total energy consumption is 0.031 ± 0.017 (n = 14), electricity recovery is 0.027 ± 0.015 (n = 15) and heat recovery is 0.029 ± 0.023 (n = 12). Data from the reviewed studies showed no significant difference in energy consumption for mesophilic and thermophilic digesters. It should be mentioned that not all datasets contained information about how the reactor was heated, which adds significant uncertainty to the picture. We observed a weak correlation between the amount of energy consumed and recovered with the TS input of the wet weight (Figure 5). The correlations are shown in Eqs. (3) – (5):

$$Energy\ consumption\ (kWh\ /\ kg\ wet\ input) = 0.0076 \times TS\ input\ (\%\ of\ wet\ weight) \quad (r^2 = 0.73) \tag{3}$$

$$Electricty\ recovery\ (kWh\ /\ kg\ wet\ input) = 0.0081 \times TS\ input\ (\%\ of\ wet\ weight) \quad (r^2 = 0.80) \tag{4}$$

$$Heat\ recovery\ (kWh\ /\ kg\ wet\ input) = 0.0069 \times TS\ input\ (\%\ of\ wet\ weight) \quad (r^2 = 0.87) \tag{5}$$

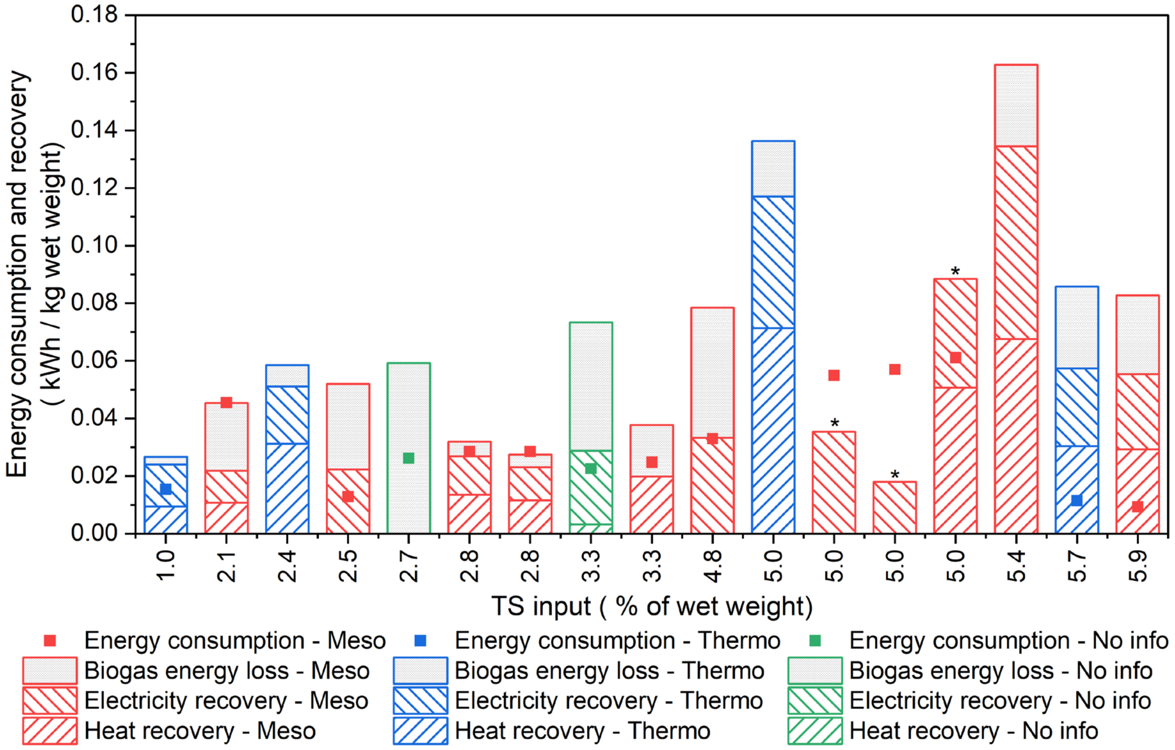

Fig. 5. Anaerobic digestion of sewage sludge: Energy consumption and recovery reported for full-scale digesters as a function of TS in input. Biogas energy loss: difference between energy content of the generated biogas and recovered electricity and heat. (*: No data on gas generation).

3.2 Composting

Regarding sewage sludge composting, we found 35 datasets representing full-scale or pilot-scale data. All composting datasets were based on dewatered sludge with a solid content ranging from 12 – 33% TS (20.4 ± 5.1 % TS, n = 28). Both raw and digested sludge can be composted: 19 datasets were found on raw sludge and 16 datasets on anaerobically digested sludge. In the papers reporting on sludge composting, raw sludge had 31 – 79% VS (66.5 ± 12.4 % VS, n = 12) and digested sludge 19 – 65% VS (43.7 ± 13.8 % VS, n = 7). Where possible, we distinguish between the two sludge types in our interpretation of the results.

The results for composting are presented in the following paragraphs in terms of amounts of bulking materials used, compost composition, off-gas and energy consumption.

3.2.1 Composting: Bulking materials

In full-scale composting plants, bulking material is added to the dewatered sludge at ratios of 0 – 130 % on a wet weight basis and 0 – 300 % on a TS basis. The ideal bulking material is dry with high VS content, retains its bulking function throughout the composting period, is by itself an easily available organic waste product and can be left partly degraded in the compost. Scarce and stable bulking material of a certain size can be removed from the final compost and re-used. The full-scale plants found in the literature, according to their own wording, used plant prunings, green waste, sawdust, wood chips, wheat straw and coffee-roast waste.

It is likely that organic bulking material, in part, is also found in the compost due to degradation and physical wear, which prevents accurate estimates, based on the reported data, of how much of the VS in the sludge degrades during composting. Figure 6 presents the VS content in the compost as a percentage of VS in the input sludge, plotted as a function of the amount of bulking material added during the composting process. The first four data points represent composting with no bulking material and show that 50 to 90% of VS in the input sludge is found in the compost, thus suggesting the degradation of VS in the range 10 – 50%. Values within the same range (actually 16 – 46%) were found in laboratory-scale experiments using stable bulking materials such as bamboo charcoal, ceramics and pumice (Li et al., 2019; Wang et al., 2018b; Wang et al., 2019; Wu et al., 2015). Figure 6 shows that in many cases bulking material contributes significantly to the VS content of the compost; VS in the compost is higher than that in the composted sludge. In some of the reported datasets in Figure 6, the VS content is as low as 25% (see Figure 6), suggesting that VS in the sludge could be degraded by up to 75%. The nature of the bulking material, time as well as aeration are likely to play a role here. Since we cannot account for any contribution to VS by the bulking material, the data do not allow us to conclude on the higher percentage degradation of sludge VS during composting.

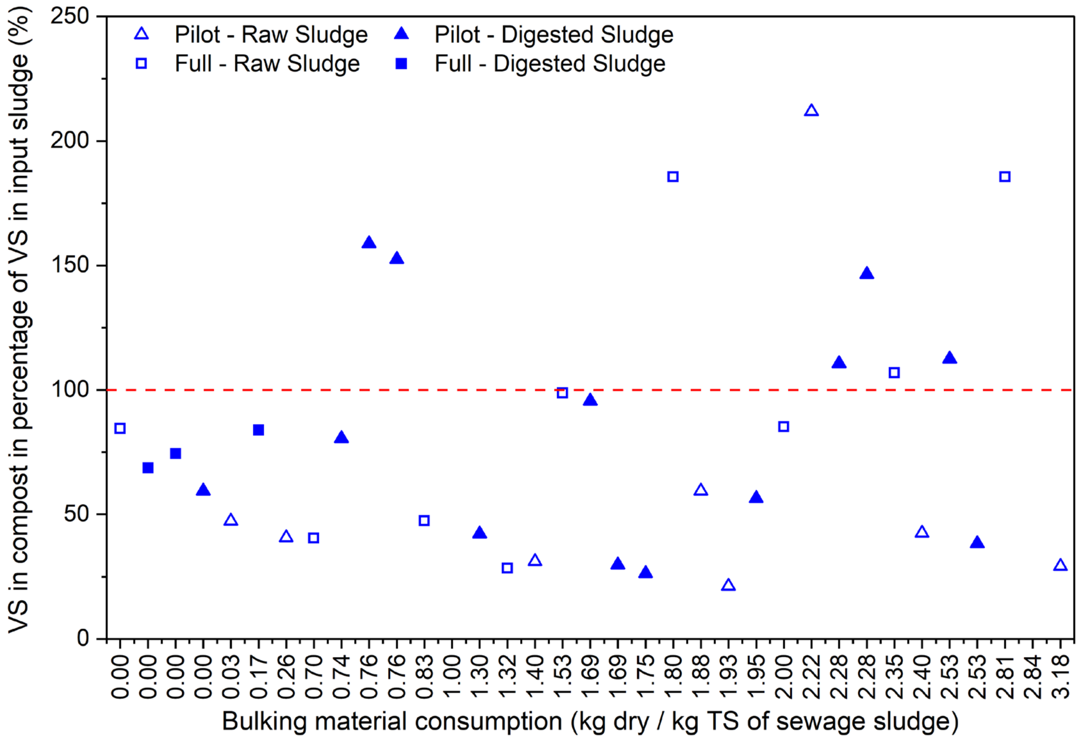

Fig. 6. Composting of sewage sludge: VS in compost as a percentage of VS in input sludge and as a function of added bulking material.

3.2.2. Composting: Compost quality

The quality of sewage sludge compost varies significantly, but there are still differences between compost based on raw sludge and on digested sludge. The main characteristics, are shown in Table 1, including nutrients content (here N and P), which determines together with carbon content the value of the compost as a fertiliser and soil amendment material. We found no data on the potassium (K) content of sewage sludge compost.

In 15 cases, full-scale plants and pilot-scale experiments reported the N content of the input sludge, the bulking material and the compost, thereby allowing for estimating the recovery of nitrogen in the composting process. Data for P were found in two cases. The recoveries varied significantly, with averages for raw sludge composting of 55.2 ± 21.4 % (n = 10) for N and 30.5 % for P (n = 1) (Gutierrez et al., 2017) and for digested sludge composting 58.4 ± 34.9 % (n = 4) for N and 22.5 % for P (n = 1) (Naserian et al., 2021). Assuming that the bulking material degrades less during composting than sludge, the numbers suggest losses of N in the sludge in excess of 40%.

Table 1. Composting of sewage sludge: Compost characteristics

Sludge composted	Water content (% of wet weight)	VS (% of TS)	C (% of TS)	N (% of TS)	P (% of TS)
Raw sludge	45.9 ± 9.8 (n=17)	55.9 ± 18.8 (n=17)	30.2 ± 11.0 (n=7)	1.9 ± 0.5 (n=14)	5.2 ± 7.7 (n=3)
Digested sludge	35.3 ± 11.5 (n=13)	37.4 ± 17.1 (n=13)	27.6 ± 9.4 (n=3)	2.5 ± 0.5 (n=4)	1.1 (n=1)

Variations in water and VS content are illustrated in Figure 7. The higher VS content in compost from raw sludge is consistent with our earlier observations, and higher VS content also suggests a higher ability to contain moisture.

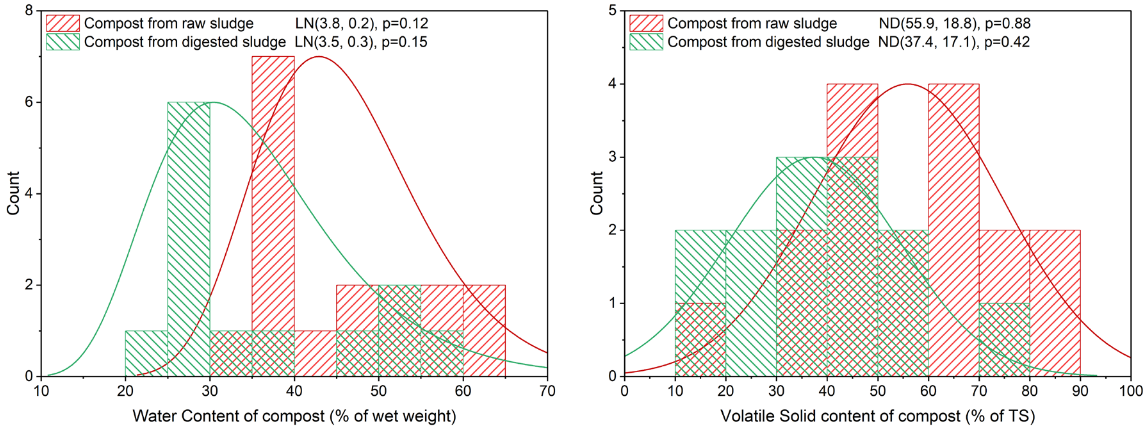

Fig. 7. Composting of sewage sludge: Distribution of water content and VS content of compost, based on raw sludge and digested sludge (LN: Lognormal distribution; ND: Normal distribution).

3.2.3 Composting: Off gases

In a few cases, off-gases from sewage sludge composting have been characterised and related to the mass of sludge. The reported data are presented in Table 2 as cumulative emissions per kg TS. CO_2 emissions are directly coupled to the degradation of VS, while it is interesting to note that the other gases are reduced compounds emanating from an aerobic technology. Methane (CH_4) as well as dinitrogen oxide (N_2O) are strong greenhouse gases. The C/N ratio, bulking material, time and aeration rate all influence off-gas emissions (Jiang et al., 2019; Shen et al., 2020; Yuan et al., 2016). The two datasets reporting on CH_4 emissions indicate, when considering the reported CO_2 emissions, that between 0.5% and 12% of the degraded carbon is emitted as CH_4. Ammonia emissions are large according to Han et al. (2018b), Li et al. (2021) and Shen et al. (2020), who reported 5%, 13% and 22 % losses of N in off-gases, respectively. Dinitrogen oxide (N_2O) contributed up to 2% (Han et al., 2018b; Li et al., 2021).

In some cases, it has been suggested to reduce anaerobic off-gases by adding specific bacterial communities (Xue et al., 2021), polypropylene (Li et al., 2021), chemicals (Li et al., 2020; Shou et al., 2019) and vesuvianite (Jiang et al., 2019). Odours are part of off-gases (González et al., 2019; Han et al., 2018a; Zhao et al., 2019), but odour emission is difficult to relate to the mass of sludge being composted (González et al., 2020; Nie et al., 2019; Robledo-Mahón et al., 2019). Off-gas emissions can be reduced by pumping air through biological filters (Almarcha et al., 2014).

Table 2. Composting of sewage sludge: Cumulative emissions of off-gases from composting

Scale	Bulking material	C/N	Sludge Type	VS degradation ratio %	Time	NH_3	H_2S	CO_2	CH_4	N_2O	Reference
					days	mg / kg TS of sludge input					
Full	organic	11.6	Raw	74	23	4700					(Shen et al., 2020)
Full	organic	7.7	Raw	49	30	8080		216260	400	395	(Han et al., 2018b)
Full	organic	7.3	Raw	ND	30	6000	38				(Han et al., 2019)
Full	organic	7.9	Raw	19	28		57				(Han et al., 2018a)
Full	organic	7.9	Raw	25	25		63				(Han et al., 2018a)
Lab	organic	10.6	Digested	ND	36	10000		183900			(Zukowska et al., 2019)
Lab	inorganic	6.4	Raw	17	25	3900		1300			(Wu et al., 2015)
Lab	inorganic	14.4	Raw	ND	25	4565		354195	15735	335	(Li et al., 2021)

3.2.4 Composting: Energy consumption

Energy consumption figures for mixing, turning and air supply at full-scale plants were reported only in two cases. Electricity is primarily used for the air supply, while diesel is used for the turning machine. Tachibana et al. (2011) composted digested sludge in windrows and used 0.24 kWh and 0.02 kg diesel per kg TS input, while Wang et al. (2020) composted raw sludge in aerated windrows and used 0.37 kWh per kg TS input; no diesel consumption was reported in the latter case.

In a full-scale scenario, a rise in temperature is caused by microbial activity, and no external heating is needed (Zukowska et al., 2019). However, in small-scale experiments, external heating has been applied (Oazana et al., 2020).

3.3 Summary of inventory data for biological treatment of sludge

A summary in terms of key inventory characteristics and typical numbers is shown in Table 3 in order to illustrate the main differences between anaerobic digestion, composting and combined digestion and composting.

Table 3. Biotreatment of sewage sludge: Typical data illustrating the characteristics of anaerobic digestion, composting and a combination thereof (details provided in the text). The data in the right column represent the sum of the two other columns, disregarding that after digestion, the amount of TS composted is reduced.

Process characteristic	Digestion No oxygen	Composting Excess oxygen	Digestion + composting
Input			
Sludge, kg TS	1	1	1
Air, m^3 /kg TS	0	High: no data	High: no data
Bulking material, kg /kg TS	0	0.8	0.8
Heat, kWh/kg/TS	1.6	0	1.6
Electricity, kWh/kg TS	0.6	0.3	0.9
Fuel, l diesel/kg TS	Marginal	0.025	0.025
Output			
Digestate, solid, kg/kg TS	0.7	0	0
Digestate, liquid, kg/kgTS	25	0	25
Compost, kg/kg TS	0	0.7	0.5
Biogas, m^3/kg TS[a]	0.3[a]	0	0.3[a]
Off-gas, m^3/kg TS[b]	0.7[b]	High: no data	0.7[b] + high
Recovered heat, kWh/kg TS[b]	0.7[b]	0	0.7[b]
Recovered electricity, kWh/kg TS[b]	0.8[b]	0	0.8[b]

In digestion, the values marked “a” are zero if the biogas is combusted, which then generates the outputs marked “b” – and vice versa.

In anaerobic digestion, biogas production varied greatly among the reported data. A useful correlation was identified between the amount of methane produced per kg volatile solids and the percentage of volatile solids degraded. We looked for significant differences in biogas production for mesophilic and thermophilic digesters as well as with respect to the scale of the digesters, but we found none worth reporting. Methane content varied significantly but no significant differences were observed between mesophilic and thermophilic digesters. Very few data were available on either digestate or energy issues, revealing only very uncertain quantitative information.

In composting, making accurate estimates of the degradation of volatile solids was not possible, since organic bulking materials added to the process for practical reasons were also part of the final compost product. This bulking material was reported as being used in quantities between zero and 300% on a dry basis; nevertheless, the data still indicated that composting may reduce the VS content of the sludge by up to 75%. Compost quality was different when based on either raw or digested sludge. i.e. the former had higher organic content and higher water content. Data on emissions in to the air (CH_4, NH_3 and N_2O) were few, but they indicated a significant loss of nitrogen. We were not able to quantify how well potassium and phosphorus were recovered, but sludge loses at least 40% of its nitrogen content during composting, which points to the need for more data on mass balances, including gaseous emissions. We were not able to relate any observed difference to the composting technology.

Although we observed difference in final compost quality for compost based on raw sewage sludge and compost based on digested sludge, no significant difference was observed regarding the technology in terms of bulking material, off-gasses or energy consumption.

4. Conclusions

The biological treatment of sewage sludge was reviewed herein with the purpose of establishing inventory data for all sludge treatment inputs and outputs. We identified 193 scientific papers, 87 of which contained inventory data, resulting in 64 datasets on anaerobic digestion and 35 datasets on composting. We found that the inventory data evaluated herein can be useful in feasibility studies on biological sludge treatment, in comparing technologies and as a basis for evaluating the performance of a specific biological sludge treatment plant.

However, there is a need for more complete datasets on full-scale technology performance, which would thus help establish full inventories and aid in identifying differences in technology and operational conditions. This review clearly shows significant data gaps in this regard.

In order to obtain a full inventory for anaerobic digestion of sewage sludge, more scientific documentation in full-scale is needed regarding the energy use in reactor heating, loss of methane from plants and storage facilities, and digestate in terms of volume and composition, for example as to the solid and dissolved contents important for the further treatment of the digestate. Very few of the studies reported on extensive degradation of the organic matter in the sludge, actually only three studies observed over 60% degradation of VS. This indicates that much of the data available of anaerobic digestion of sewage sludge comes from non-optimal processes. This calls for more data on well-functioning anaerobic digestion of sewage sludge, showing high VS degradation and high methane generation. This could also suggest that in life-cycle assessment of anaerobic digestion technology, inventory data should be carefully evaluated prior to use.

In order to obtain a full inventory for composting of sewage sludge, more scientific documentation in full-scale is needed regarding use of bulking materials. The reviewed studies showed very large variation in the amount of bulking material used, but it was unclear whether large ratios of bulking materials were needed for the composting process as such or were used because bulking materials were abundant and in themselves constituted a waste management problem. The significant variation in degradation of the organic matter in the sludge as well as the nitrogen loss during composting could not be related to differences in the technology nor in the operation of the composting process. Air emissions during composting were significant but not well quantified. This is a must in future scientific investigation of sewage sludge composting.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary information

Supplementary information is available online.

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