Recycling of Biowaste: Experience with Collection, Digestion, and Quality in Germany

Klaus Fricke, Christof Heußner, Axel Hüttner, and Thomas Turk

Abstract Only cascading use can ensure higher sustainability in the recycling of biodegradable waste materials (biowaste) compared to pure thermal and/or energetic utilization types. Cascading use means, in a first stage, that energy is skimmed off by a fermentation process. In a second stage, products used as organic fertilizers and soil improvers are generated. This is usually done by composting. The separate collection of biowaste is a prerequisite for the production of high-quality organic fertilizers and soil improvers.

The anaerobic treatment of biowaste and green waste in Germany has not gained the importance it deserves by far, owing to its ecological advantages. This is also evidenced by the high expansion and development potential afforded by the anaerobic treatment. There is a need for action in two areas: (1) increase the amount of biowaste collected by establishing a tightly meshed nationwide expansion of the organic waste bin system and increase the collection rates and (2) channel a large proportion of the biowaste currently only undergoing composting into fermentation as well. The potential for increasing fermentation in Germany is estimated at 5.4 million tons.

Keywords Anaerobic digestion, Biowaste, Composting, Recycling, Source separation

Contents

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1 Introduction

Only cascading use can ensure higher sustainability in the recycling of biodegradable waste materials (biowaste) compared to pure thermal and/or energetic utilization types. Cascading use means, in a first stage, that energy is skimmed off by a fermentation process. In a second stage, products used as organic fertilizers and soil improvers are generated. This is usually done by composting. The separate collection of biowaste is a prerequisite for the production of high-quality organic fertilizers and soil improvers.

The controlled anaerobic digestion of organic residues has long been a common practice in wastewater treatment (sludge) and agriculture (manures, slurries). Anaerobic technologies for the treatment of solid residues like biowaste and green waste were first applied in the beginning of the 1990s. During the implementation phase of the "selective collection and utilization of biowaste" system from 1988 to 1995, biodigestion technology had not yet reached the necessary development stage. It was not until the last 10 years that biodigestion had gained importance. Initially, the reluctance to apply the technology was due to technological and economic reasons. Technical shortcomings were attributed to functional failures across the whole process (mechanical and biological), as well as to remarkably high wear and tear.

The high investment and operating costs of anaerobic processes compared to aerobic processes initially impeded the establishment of the anaerobic technology despite its numerous ecological advantages. In the meantime, anaerobic technology has been continuously developed and optimized, while technical problems have been reduced to an acceptable level. On the economic side, the Renewable Energies Act [1] provided a favorable framework for the installation of anaerobic technologies. Anaerobic processes still require higher investment costs but have become more cost-effective than in the mid-1990s. Operating costs for anaerobic and aerobic technologies are now on the same level. This is because energy revenues can be obtained with anaerobic technologies, thanks to the Renewable Energies Act. Under certain circumstances, the anaerobic processes may even provide economic advantages.

The 65% recycling quota required by the German Waste Management and Product Recycling Act [2] and the requirement for the separate collection of biowaste in force since January 1, 2015, play key roles in the increased development of both biowaste processing and anaerobic technologies.

2 Material Flow Management of Biowaste and Green Waste

2.1 Status Quo and Potential Assessment of Biowaste and Green Waste Processing

The separate collection of biowaste and green waste in Germany has reached a high level of implementation. However, the proportion of energy produced from these waste types is still comparatively small. Biowaste and green waste are mostly processed by composting. According to the German Federal Statistical Office, 9.8 million tons of biowaste and green waste were collected in 2014 (Fig. 1). Processing takes place at 990 composting facilities and approximately 100 anaerobic treatment plants. Around 2 million tons of biowaste and green waste are treated in anaerobic facilities. The quantities of previously collected, anaerobically processable biowaste and green waste still presently channeled to composting account for 3.9 million additional tons per annum (Table 1). With the nationwide implementation of separate biowaste collection mandated by the German Waste Management and Product Recycling Act on January 1, 2015 [2], this amount can be increased by another 1.5 million tons to about 5.4 million tons a year.

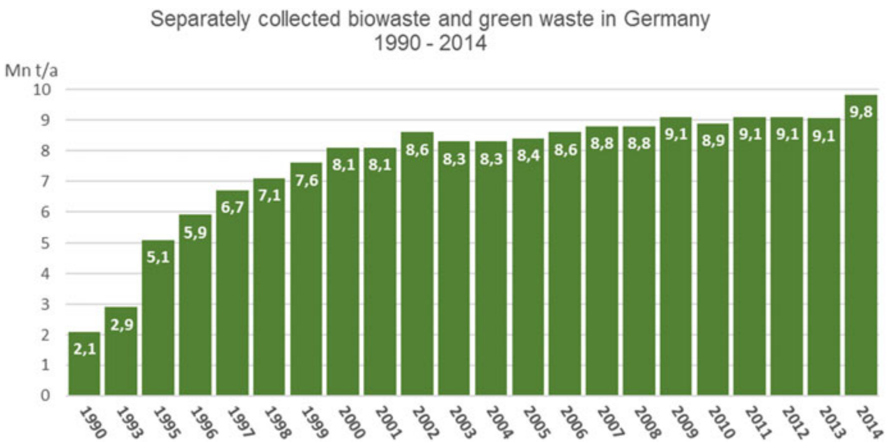

Fig. 1 Separately collected biowaste and green waste in Germany 1990–2014

Table 1 Projected total quantities of biowaste and green waste also available for anaerobic digestion in Germany

	Biowaste (t/a)	Green waste (t/a)	Total (t/a)
Amount of biowaste and green waste in 2014 (separately collected)	4,602,900	5,228,600	9,831,500
Fermentable potential (85% of biowaste, 30% of green waste)	3,912,465	1,568,580	5,881,045
Existing fermentation capacity for biowaste and green waste			Approximately 2,000,000
Additional expansion potential for anaerobic digestion of already separately collected biowaste and green waste			3,881,045
Additional expansion potential for anaerobic digestion given nationwide implementation of the organic waste bin			1,500,000
Aggregate additional potential for anaerobic digestion of biowaste and green waste			**5,381,045**

2.2 *Feedstock Quality and Quantity for Anaerobic Digestion*

Biowaste and green waste are subject to seasonal fluctuations in quantity and quality that create sizing problems for composting plants. In Germany, supply peaks are mostly observed in the summer and autumn, encumbering attempts to maintain constant utilization capacity. Besides suboptimal fermenter utilization, the low performance of biogas production can impair CHP unit utilization and, consequently, reduce electric efficiency. In the same way, the biological process is affected by fluctuations in feedstock quantity and quality, which in turn results in a decrease in gas production and reduced process stability. Green waste also undergoes impressive annual variations in amount and material composition. The problems relating to fermenter utilization and gas production described above are aggravated when suitable green waste is channeled into the anaerobic treatment facility. Late spring and summer are the seasons for digestible green waste, like grass cuttings, with comparatively high biogas potential. In the autumn, large quantities of dead leaves are available, albeit with low biogas potential. In winter, almost no green waste is available.

For the anaerobic treatment of biowaste and green waste to be efficient, a balanced supply throughout the year has to be targeted, at least in Germany and countries with similar climatic conditions. In other countries with seasonally balanced climates, these problems are not extant or only exist to a limited extent.

Organic kitchen waste has a significantly higher gas potential than garden waste. Leaves have particularly low gas potential (Table 2). However, collection rates for kitchen waste are considerably lower than for garden waste, as practiced in Germany. Therefore, measures need to be taken to improve the collection of kitchen waste, such as public relations work and controls to ensure proper disposal and collection. In

Table 2 Specific biogas production and quality of different feedstocks as a function of digester input

Raw material	Quantity (m^3/t fermenter input)	CH_4 (vol.-%)
Biowaste (mixture of kitchen and garden waste)	75–136	53–63
Biowaste (kitchen-generated)	123–178	53–68
Green waste (without wooden components)	40–90	50–61
Org. fraction of mixed waste (MSW)	100–174	57–62

urban areas with no or only minimal private garden areas, the high gas volumes for kitchen waste must be used for the plant sizing, as shown in Table 2.

2.3 Compost Quality Generated from Separate Collection and Mixed Waste (MBT)

Fundamentally, the question must be discussed as to whether it is imperative to collect kitchen and garden waste separately or whether it is also possible to sustainably utilize the kitchen and garden fractions from mixed waste.

A study on compost quality conducted by the European Commission's Joint Research Centre in ISPRA supplies valuable information relating to the discussion of this topic. ISPRA ran a spot-check and analysis within 15 European countries by taking 113 samples and analyses made from sludge compost, biowaste compost, green waste compost, and compost from mixed waste and/or mechanical biological treatment [3]. This study aimed to provide robust data for the end-of-waste (EoW) discussion. Likewise, the findings ought to allow conclusions about whether it is imperative that kitchen and garden waste be collected separately or whether it is also possible to sustainably utilize the kitchen and garden fractions from mixed waste.

Over the past few years, the reprocessing and conversion technology used in compost generation have improved markedly. This has allowed the concentrations of physical impurities and heavy metals in the compost generated from mixed waste to be reduced substantially. Nevertheless, compost from separate collections continues to have a significantly better quality than compost from mixed waste; this particularly applies to the two main parameters of physical impurities (glass, metal, plastic particles <2 mm) and heavy metals.

Figure 2 plots the physical impurities in compost samples collected by JRC and sent by plants. The red bar represents the proposed maximum value for EoW product criteria (Co, compost; BW, source-separated biowaste and green waste; GW, source-separated green waste; SS, sewage sludge; MBT, mechanical biological treatment). Compared to compost generated from mixed waste by MBT, separately collected biowaste composts contain markedly lower concentrations of physical impurities.

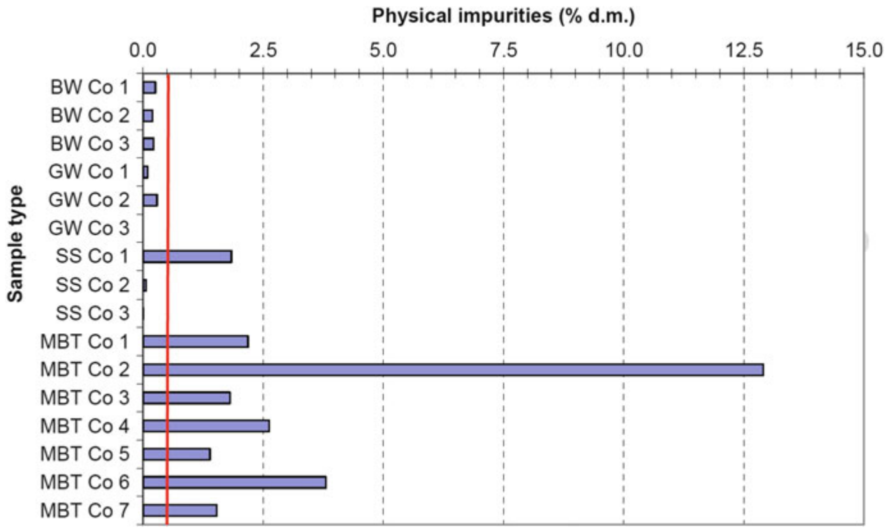

Fig. 2 Physical impurities (glass, metal, and plastic particles >2 mm) in compost samples collected by JRC and sent by plants

Table 3 presents the heavy metal loads of composts generated from mixed waste as compared with those from separate collections. The comparison shows that compost from source-separated collection exhibits the lowest overall heavy metal concentrations. When compared with the compost quality from the 1970s and 1980s, as was produced from mixed waste, for example, in Germany, there has been a marked decline in heavy metal concentrations.

The comparative analysis of the aforementioned studies by JRC-IPTS [3] yielded similar findings:

- "**Hg**: All samples met the proposed limit of 1 mg/kg dry matter.
- **Cr**: Nearly all samples met the proposed limit of 100 mg/kg dry matter, except one sewage sludge compost sample, one MBT compost sample, and one compost-like output from an MBT installation destined for landfilling.
- **Pb**: Nearly all samples met the proposed limit of 120 mg/kg dry matter, except four MBT compost samples.
- **Cd**: Most samples met the proposed 1.5 mg/kg dry matter limit value, except one green waste compost sample, one sewage sludge compost sample, four MBT compost samples, one digestate sample, and one other sample.
- **Ni**: Most samples met the proposed 50 mg/kg dry matter limit value, except four separately collected biowaste compost samples, one green waste compost sample, one sewage sludge sample, and one MBT compost sample.
- **Cu**: Compost from source-separated biowaste or green waste generally met the proposed limit value of 100 mg/kg dry matter, except for two samples (one in each category). Sewage sludge compost, MBT compost, and digestate hardly meet the

Table 3 Concentrations of heavy metals for compost from source-separated organic waste and from MBT of mixed waste (in mg/kg dry matter)

	Spain mixed waste compost MBT[a]	France mixed waste compost MBT[b]	France biowaste compost[b]	Austria biowaste compost[c]	Germany biowaste compost[d]	Germany mixed waste compost[e]
Data	2013	2007	2009	2010	2013	1980
CD	1.4	1.4	0.3–0.4	0.57	0.42	5.5
Cu	158	152	58–65	62	39	274
Hg	0.3	0.6	0.1–0.3	0.2	0.24	2.4
Ni	29	31	9–18	23	13.4	45
Pb	97	138	32–32	31	31.2	513
Zn	351	476	128–192	204	169	1,570

[a]Stabilized MBT – material: SCT, personal communication Carrera, 2013
[b]Stabilized MBT – material: Veolia/Copin – personal communication. Biowaste compost: two individual composting plants, personal communication to Bart. Documents from the French Quality Assurance Project ASOA, 2007
[c]Database of the Austrian Compost and Biogas Association; Data from 2010 to 2012
[d]Database of the German Federal Compost Association (BGK), personal communication, 2013
[e]Fricke et al. [4]

proposed limit values, with measured median values situated around the proposed limit value.

- **Zn**: Compost from source-separated biowaste or green waste generally met the proposed limit value of 400 mg/kg dry matter, except for one green waste compost sample. More than 20% of the sewage sludge compost, MBT compost, and digestate samples did not meet the proposed limit values."

Table 4 shows the trend in heavy metal concentrations in German biowaste composts. In recent years, a significant reduction in the burden has taken place. The causes are complex. A major source of the burden of composted raw materials includes wet deposits from air emissions that contaminate the composted raw materials directly and/or indirectly through the soil (primary source). An improvement in the concentrations of relevant heavy metals has been observed since the 1990s. This particularly applies to lead, mercury, and cadmium. The reduction in heavy metal deposits has most likely contributed to the decline in heavy metal concentrations in biowaste composts. Since there was no change in the grade of physical impurities during those years in Germany, this reduction can be excluded as a reason for the improvement, as can better pretreatment technology for eliminating physical impurities and contaminants, respectively. Hence, it is suggested that the heavy metal burden in kitchen and garden waste is declining.

Table 4 Heavy metals trends in biowaste composts in Germany (mg/kg dry matter)

	Biowaste compost 1991	Biowaste compost 1999	Biowaste compost 2012	Biowaste compost 2016	
	Median $n = 153$	Median $n = 2.510$[a]	Median $n = 2.691$[a]	Median $n = 3,345$[a]	Changing to 1991 (%)
Pb	63.2	52.7	31.2	31.3	−51
Cd	0.79	0.51	0.42	0.42	−47
Cr	33.0	25.6	22.0	20.5	−38
Cu	39.3	49.6	39.0	39.5	−0
Ni	18.6	15.9	13.4	13.1	−28
Hg	0.25	0.16	0.10	0.11	−70
Zn	182.9	195.0	169.0	160.1	−12

[a]Data from the German Federal Compost Association

3 Anaerobic Treatment Technology and Processes

3.1 *Classification of Anaerobic Digestion Technologies/ Processes*

The technologies and processes used for the anaerobic treatment of solid waste are different from the ones used for the anaerobic treatment of residues from wastewater treatment plants, residues from agricultural and industrial production, and renewable feedstocks. The differences become apparent in the anaerobic processes and in pre- and post-processing. The classification is based on the biodigestion process and the feeding process used for the substrate and not on the conditioning technology for the feedstock. Percolation under aerobic conditions is classified as wet conditioning; digestion itself is conducted in a wet anaerobic process. Processes that use presses are classified as dry conditioning, and wet or dry processes are applied depending on the desired quality of the output. The technologies and processes used for anaerobic treatment can be organized according to the different types depicted in Fig. 3. This system is the basis for describing the status quo on anaerobic treatment of biowaste and green waste in Germany.

3.1.1 Mesophilic and Thermophilic Processes

Degradation during anaerobic processes takes place due to the action of different organisms whose nature and performance are dictated by the process temperature. Optimum performance of the microorganisms occurs within two narrow temperature ranges. For practical applications, the relevant temperatures are in the mesophilic (approximately 34°C–42°C) and thermophilic (approximately 50°C–60°C) ranges. All processes can be operated with mesophilic temperatures, as well as with thermophilic temperatures.

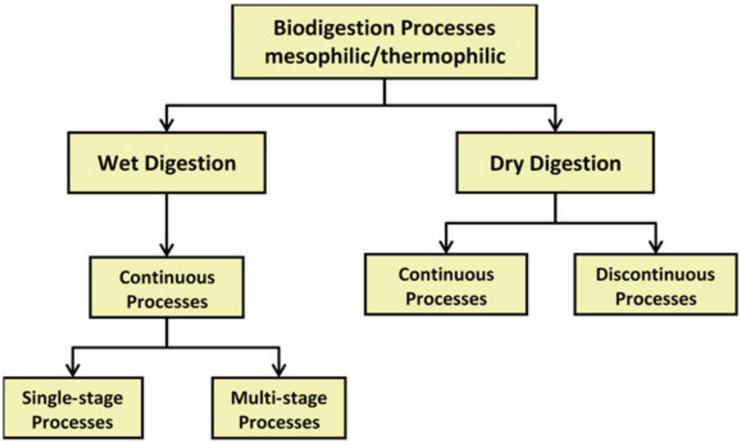

Fig. 3 Types of anaerobic treatment technologies and processes

3.1.2 Dry and Wet Processes

Anaerobic digestion processes can be divided into dry or wet, according to the dry matter content in the substrate fed into the fermenter. Dry process technologies can be further differentiated into continuous and discontinuous operations. Dry processes are operated with dry matter contents above approximately 30%. There is no limitation on dry matter content, which is determined by the input material. Biowaste and green waste usually have dry matter contents of 35%–50%. Wet processes are characterized by dry matter contents below 12%–15%, and the lowest values, for instance, in fixed-bed reactors, are below 1% dry matter.

3.1.3 Continuous and Discontinuous Dry Processes

Continuous processes are characterized by the addition of feed and the removal of corresponding amounts of digested substrate at regular intervals. A more or less continuous biogas production of constant quality is the result. In discontinuous processes – also known as batch processes – the fermenters (tunnels) are filled with raw substrate or sometimes mixed with predigested material and then closed. Over a period of 3–4 weeks, the material is irrigated with process water or percolate. This triggers the anaerobic degradation process and causes biogas to form in the tunnels and percolate reservoirs. Irrespective of an additional wet digestion stage of the percolate, the discontinuous processes are classified as dry processes – whereas some ambiguity cannot be avoided.

3.1.4 One-Stage and Two-Stage Processes

With the participation of various microorganisms, anaerobic degradation occurs in four successive steps: hydrolysis, acidification, acetic acid formation, and methanation. In single stages, all degradation steps take place in one vessel. Therefore, the environmental conditions cannot be adapted specifically to the individual requirements of the different microorganisms involved in the degradation. In two-stage processes, the hydrolytic step and the ongoing formation of low-molecular-weight acids take place separately from the methanation step. The separation of the steps allows better adaptation of the environmental conditions to the individual requirements of the microorganisms, however, and results in higher expenditures on technology, construction, and operations.

Conventional two-stage processes are restricted to wet processes. Process combinations consisting of an upstream aerobic process stage and a subsequent anaerobic process stage are known as quasi-two-stage processes. The most acidifying bacteria are facultative anaerobic and can metabolize in both the presence and absence of oxygen. The upstream aerobic stage is designed to bring about more effective hydrolysis and acidification. Heating to the desired mesophilic or thermophilic temperature levels can be achieved by the upstream aerobic process stage. Consequently, these processes are classified as one-stage processes in the system.

3.2 Status Quo of Anaerobic Digestion Technologies and Processes

By the end of 2014, 100 facilities with a processing capacity of about 2 million tons of biowaste and green waste had gone into operation. A total of 20 facilities operated with the wet process and 80 with the dry process. Of the facilities operating with the dry process, about 50% are continuously operated and 50% run the discontinuous process. The dominating position of the dry processes is also reflected by the single- and two-stage processes, because the conventional two-stage processes are restricted to wet processes. Only nine of 100 facilities run a two-stage process. Fifty-seven percent of the facilities operate within the mesophilic temperature range and 43% at thermophilic temperatures. The majority of the dry continuous processes are operated at thermophilic temperatures, whereas dry discontinuous processes are mainly operated at mesophilic temperatures.

In terms of the historical development of the construction of anaerobic treatment facilities for biowaste and green waste, the actual beginning of the anaerobic treatment of biowaste and green waste dates back to the mid-1990s. Before that time, only experimental and demonstration facilities had been in operation (Fig. 4). The most intensive construction of new facilities occurred after 2003.

Impressive advancements in process engineering and operation modes have been observed in the past few years. In the 1990s, the construction of wet processes was

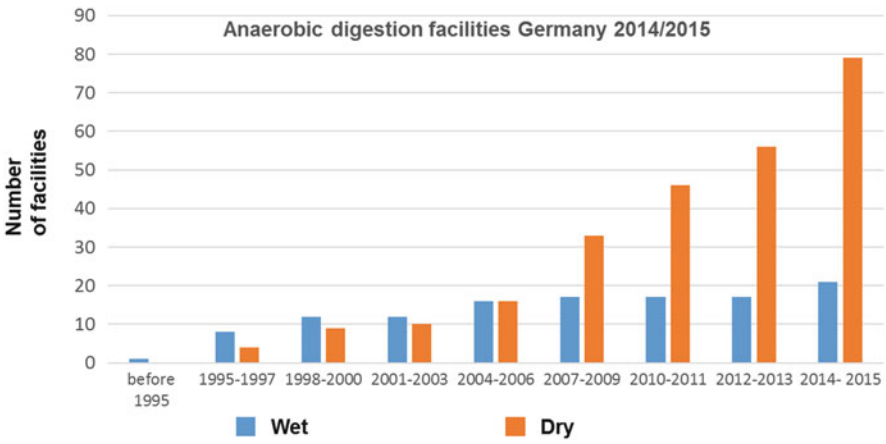

Fig. 4 Years after starting the operation of anaerobic treatment facilities for biowaste and green waste

predominant; half were single-stage and the other half, two-stage processes. In the 2000s, mostly dry processes were installed. The boom of dry discontinuous processes commenced in 2006, with 50% of the dry processes operating with the dry discontinuous process. In the beginning, this development was supported by the German Renewable Energies Act (EEG) based on subsidized dry processes [1].

In relation to single-stage or two-stage process engineering and technologies, the development was clearly in favor of single-stage processes. In the past several years, not one two-stage facility for the anaerobic treatment of biowaste and green waste has been put into operation, and no two-stage process which is among the facilities is under construction. Some well-known manufacturers only offer two-stage processes explicitly upon request.

A tendency toward thermophilic processes can be observed. For instance, at several locations with dry discontinuous processes, the transition to the thermophilic temperature range is envisioned. According to specialized manufacturers, the majority of facilities under construction plan to implement thermophilic processes. This is expected to achieve substrate hygienization as well as a higher biogas production.

The processing capacities of the anaerobic treatment facilities for biowaste and green waste currently in operation are all below 50,000 tons per annum. The majority of facilities installed capacities on the order of 10,000–30,000 tons per annum. Compared to waste incineration plants and composting plants, these capacities are low. The facilities currently under construction have higher capacities, mainly in the range of 30,000–70,000 tons per annum.

4 Energy Production

4.1 Basis for Calculation

The energy efficiency assessment is based principally on the energy production from the biogas produced and the energy consumption of the anaerobic digestion process. Consequently, this has to be considered in the overall context together with other factors, such as availability of the facility, lifetime of the equipment, and the energy requirements for construction and machines (cumulative energy requirement, CER).

The means for biogas quantities and methane content produced by the different technologies and processes are listed in Table 5. Dry continuous processes yield slightly higher quantities than wet processes. The high value observed for thermophilic wet processes is a singular observation and therefore hardly influences the mean. Dry discontinuous processes have lower biogas yields. The yield data in Table 5 refer to digester input, although relating biogas yield to the input of the facility is more meaningful because this value describes the real amount of energy produced per mg of biowaste. In wet and dry continuous processes, an average of about 20% (12%–30%) of the biowaste is separated during the preparation stage – prior to the anaerobic stage – and directly fed to the composting stage. Due to the separation of heavy components and grit, wet processes tend to show higher values. In dry discontinuous processes, the corresponding mean only approximates to 7% (0%–10%). Conversion factors have to be considered in order to convert the values (fermenter input) according to the input to the facility.

The quantities input into the facility decrease the specific biogas and methane quantities produced. In discontinuous processes, the specific biogas yield is only slightly reduced due to the lesser volume of waste separated prior to the anaerobic stage. However, the methane yield is more relevant for the energy assessment. Wet processes show higher concentrations of methane in the biogas, i.e., of about 63% v/v, compared to dry processes that reach mean values between 56 and 59% v/v. Since wet processes produce higher methane yields than dry continuous processes, the specific methane yields of both of these processes are almost at the same level. The mean specific methane yields of dry discontinuous processes are approximately 20% below the respective values of the continuous processes.

Thermophilic processes – considering the usually employed retention times – obtain impressively higher biogas and, therefore, higher methane yields across all technologies and processes (Table 5 and Sect. 5.1.3).

The following calculations are based on the data from Table 5. Combined heat and power (CHP) units are installed on more than 90% of the facilities in Germany. Electric and thermal efficiencies of 38% and 46%, respectively, were used for the calculation (see also Sect. 5.2).

For the assessment of the inherent energy consumption of anaerobic treatment facilities, not only the electricity consumption but also the fuel consumption of mobile equipment such as wheel loaders, mobile screens, and shredders have to be taken into

Table 5 Specific biogas and methane yields of different anaerobic technologies and processes for treatment of biowaste and green waste relative to the input to digesters and facilities [5]

Process		Biogas volume (m^3/t input fermenter)	Biogas volume (m^3/t input facility)	Methane content (%)	Methane volume (m^3/t input facility)
Wet	Total	111	89	63	56
	One-stage	106	85	62	53
	Mesophilic	100	80	62	50
	Thermophilic	130	104	63	66
	Two-stage	115	92	63	58
	Mesophilic	115	92	63	58
	Thermophilic	n.a.	n.a.	n.a.	n.a.
Dry	Continuous	122	98	58	57
	Mesophilic	109	87	59	51
	Thermophilic	123	99	58	57
	Discontinuous	87	81	56	46
	Mesophilic	87	81	56	45
	Thermophilic	91	85	56	48

account. Very little information is available concerning diesel fuel consumption; however, the obtained data correspond to our own findings. The diesel fuel consumption per mg of input into the facility, for intensive wet and dry processes and for dry discontinuous processes, was estimated at 1 and 1.5 L, respectively. The higher diesel consumption of dry discontinuous processes is due to loading and unloading the fermenters with a wheel loader. The energy content of the consumed diesel fuel is converted to kWh and added to the electricity consumption.

Based on the collected data, the wet processes have a higher overall energy consumption (combined electricity and diesel fuel consumption), at 65 kWh/t, compared to the dry continuous processes, at 48 kWh/t. The dry discontinuous processes have the lowest overall energy consumption, at 36 kWh/t. The low energy demand of the dry discontinuous processes, compared to the intensive wet and dry continuous processes, is mainly based on the need to prepare the feedstock, such as conditioning prior to feeding, and the nonextant demand for mixing during and dewatering after the anaerobic treatment. Compared to dry processes, the need for pumping and transporting large volumes of suspended feedstock in wet processes consumes additional energy.

The processes' inherent heat demands are based on the maintenance of the mesophilic or thermophilic process temperatures and are accordingly accounted for in the calculations of the net heat yields. The heat demands of the different technologies and processes vary widely.

4.2 Net Electricity Production

The results for the net electricity yields demonstrate that consideration of the electricity and fuel consumption improves the values for the dry, notably dry discontinuous processes. On average, the highest net yields were achieved by dry continuous processes. In spite of their low inherent energy consumption, dry discontinuous processes, because of low methane yields, do not achieve the net electricity yields obtained by dry continuous processes.

Based on the collected data, wet processes have higher overall energy consumption (combined electricity and diesel fuel consumption), at 65 kWh per ton, compared to the dry continuous processes, at 48 kWh per ton. The dry discontinuous processes have the lowest overall energy consumption, at 36 kWh per ton.

Compared to the intensive wet and dry continuous processes, the low energy demand of the dry discontinuous processes is mainly attributable to the low need for intensive mechanical pretreatment of the feedstock prior to feeding. Energy is also saved because no dewatering after anaerobic treatment is required. The need to pump and transport large volumes of suspended feedstock into wet processes consumes additional energy compared to dry processes.

The results for the net electricity yields demonstrate that the consideration of the electricity and fuel consumption improves the values for the dry, notably dry discontinuous processes. On average, the highest net yields were achieved by dry continuous processes. In spite of their low inherent energy consumption, dry discontinuous processes do not achieve the net electricity yields obtained by dry continuous processes because of low methane yields. The data obtained in this study do not correspond to the findings of the Witzenhausen Institute [6], with mean values for dry, discontinuous and dry continuous processes of 230 and 250 kWh per ton, respectively. However, it has to be taken into consideration that the data of the Witzenhausen Institute refer to the input into the fermenter. Additionally, the authors considered higher specific biogas yields, with just below 100 Nm^3 per ton fermenter input, for discontinuous dry processes.

On average, the share of the electricity and diesel fuel consumption in the electricity produced from the wet processes was approximately 31%. The dry continuous and discontinuous processes are almost at the same level, at 22% and 24%, respectively (Fig. 5).

4.3 Net Heat Production

As expected, the wet processes have comparatively high heat demands due to the necessity of heating very large volumes of water-rich feedstock and the respective heat losses. Correspondingly, dry processes have lower heat demands. In discontinuous processes, no external heating of the feedstock is necessary because the heat is provided by the aerobic decomposition processes in the initial phase of the process. In the same way, some dry continuous processes use the heat produced

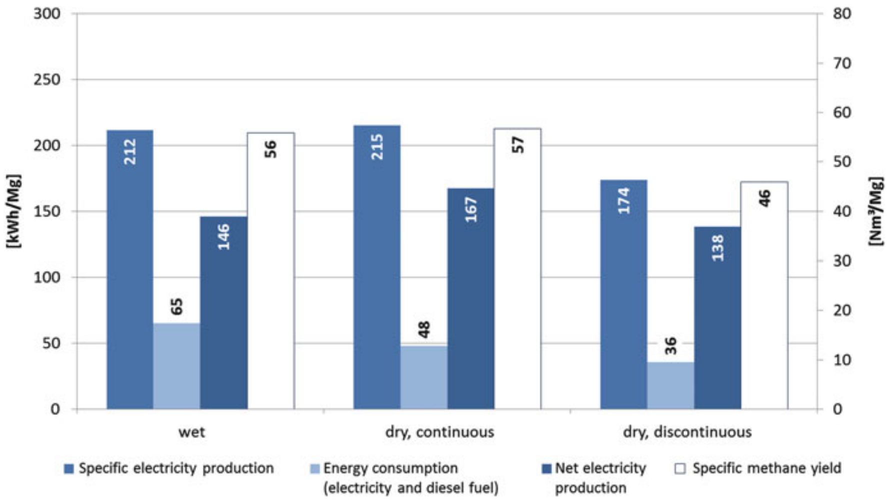

Fig. 5 Comparison of electricity production, consumption, and net electricity yields of wet and dry processes for anaerobic treatment of biowaste and green waste relative to the input into the facility

during short periods of aerobic pretreatment, usually 2–3 days, to heat up their feedstock.

Relative to the input into facilities, dry discontinuous processes have heat yields of 188–191 kWh per ton and therefore are almost on the same level with the dry continuous processes, with 173 and 191 per ton. The wet processes have heat yields of 153–204 per ton.

5 Measures for Improving Functionality and Energy Efficiency in the Anaerobic Treatment of Biowaste and Green Waste

The relevant measures include:

- Material flow management
- Technology and operation
- Biogas utilization
- Weak points

5.1 Technology and Operation

5.1.1 Pretreatment and Classification Before Anaerobic Treatment

The objective of the pretreatment of biowaste and green waste is to prepare the materials for the anaerobic treatment, as well as to discharge compounds that could compromise the process or the products. In the beginning of the anaerobic treatment of solids, such as biowaste and green waste, these were shredded to a size of <40 mm to improve the availability of organic compounds for the microorganisms and, therefore, a faster and more effective degradation of the feedstocks. In the past years, this kind of pretreatment was modified in the way that the feedstocks are shredded to a size according to the demands of the individual anaerobic processes, with grain sizes of 60–80 mm. Several facilities have since been modified accordingly, without perceivable reductions in biogas production.

In discontinuous dry processes, the waste is usually not pretreated, avoiding investment and operation costs for machinery. Furthermore, too small a grain size can impair the percolation through the piles and therefore reduce biogas production. At most dry discontinuous anaerobic treatment facilities, a wheel loader is used to mix the biowaste and green waste with digestion residues and to load the fermenters. Therefore, the feedstock is comparatively inhomogeneous, which can compromise the efficiency of the percolation process. The homogenization of feedstocks was analyzed within the scope of optimization measures at a discontinuous dry anaerobic treatment facility using a conventional mobile compost turner. The homogenization effect of a single turning process resulted in an impressively higher biogas production of 10%–15%. Equal homogenization effects can be expected by the upstream installation of a screen with grain sizes of 100–120 mm. Compared to plane sieves, drum screens result in better homogenization and, additionally, exert a shear force on the material.

If suitable green waste is to be treated anaerobically, specific logistics must be installed for separate collection, delivery, and stockpiling in order to classify the materials into batches appropriate for anaerobic treatment, composting, or energetic utilization. When mixed green waste is delivered together with tree and bush cuttings, a separate pretreatment step prior to the anaerobic stage is necessary. In these cases, shredding and mixing are helpful, because the oversize material appropriate for composting or energetic utilization accumulates at >80 mm, whereas fines of <80 mm constitute the material suitable for anaerobic treatment.

5.1.2 Loading of Fermenters

The efficiency of the anaerobic process can be increased by a continuous feeding regime of the anaerobic fermenter, resulting in stable biogas production with constant quality. Intermittent feeding only during the daylight hours and on working days results in fluctuations in biogas production. Especially during the night and on weekends, an impressive decrease in biogas production becomes apparent. Moreover, alterations in biogas quality have been observed just after feeding (decrease in methane content) and after longer periods without feeding (increase in methane content).

5.1.3 Process Temperature

Given the usual retention times, operation within the thermophilic temperature range results in an impressively higher biogas production of up to 15% and, consequently, in higher methane yields. Discontinuous dry and wet processes are mostly operated in the mesophilic range, whereas most of the continuous dry processes are operated in the thermophilic range. Therefore, the first group offers an especially high potential for optimization. The market development shows a tendency toward the thermophilic operation of anaerobic processes, and at several locations with dry discontinuous processes, while a transition to thermophilic operation is planned. According to several suppliers of corresponding facilities, the implementation of processes with thermophilic operation is planned for the majority of the facilities currently under construction. Besides the hygienization of the material, higher biogas yields are expected by thermophilic operation.

5.1.4 Dewatering

Unlike exclusively aerobic processes, anaerobic treatment processes for biowaste and green waste produce relevant volumes of process water. In terms of utilization, the biodigested residues, if hygienizated, are directly applied to agricultural areas or subjected to aerobic posttreatment for compost production. If aerobic posttreatment is planned, the residues have to be dewatered. This energy-consuming process stage is necessary for all continuous processes. Discontinuous processes usually do not need a dewatering step prior to aerobic posttreatment. The residues from the anaerobic treatment of bio- and green waste have to be dewatered to achieve a humidity of about 60%; when structural material is added, slightly higher humidity contents are acceptable. Anaerobic treatment facilities with continuous processes produce surplus water volumes per mass input of 200–500 L per ton. The dry discontinuous anaerobic treatment processes produce volumes of surplus water from the percolation of about 20–60 L per ton (Fig. 6).

Among the optimization potentials of the dewatering stage, the following measures are recommended:

- Reduce the required dewatering intensity by utilizing surplus heat for drying purposes during aerobic treatment.
- Intensify application of structural materials as long as there is no other more sustainable utilization for this material.

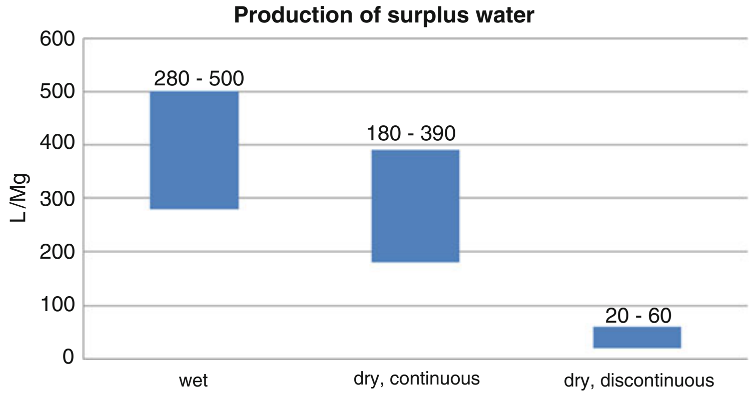

Fig. 6 Production of surplus water in the anaerobic treatment of biowaste and green waste according to technology and process type

- Hygienizate residues from the anaerobic stage and apply them directly to agricultural areas.

5.1.5 Data Availability for Energy Consumption

In none of the studied facilities were data available on the energy consumption of certain sectors or machines. Therefore, it was not possible to identify the energy conservation potentials of individual process stages.

5.2 Biogas Utilization

In more than 90% of the facilities, CHP units were in operation, and at least three of these installations also injected biogas into a microgas network, supplying gas to nearby CHP units connected to a heat distribution network or a heat consumer. The electric efficiencies were in the range of 32–42%, with a mean of 38%, and the mean thermal efficiency was 46%.

At almost 10% of the facilities, the biogas was upgraded to natural gas quality – biomethane – and fed into the public gas grid. An experimental fuel cell for biogas was installed at one facility. At another facility, the biogas was upgraded to fuel gas for garbage trucks. In 78 of the facilities, part of the surplus heat was used to heat fermenters and feedstock in order to adjust and maintain the necessary mesophilic or thermophilic temperatures. At least 17 facilities dry their digested residues or use the surplus heat-to-heat process air in order to control the composting process.

The electric efficiency of the CHP units has constantly increased during the past few years. CHP units in the range of about 500 kWh achieve efficiencies of 42%. Here, the optimization potential lies in the replacement of old units. However, as a result of increased electrical efficiencies, the thermal efficiencies of modern CHP units have decreased. The possible impacts on existing heat utilization concepts have to be assessed very critically. The corresponding thermal efficiencies are at 44%. The increased efficiency of CHP units translates into higher requirements being placed on biogas quality. In this regard, the removal of sulfur compounds has gained special importance.

5.3 Weak Points

The questionnaires and visits to the facilities focused on the weak points of the individual treatment stages, the machines, as well as of the whole system. The willingness of the facilities' operators to provide information varied widely, as was to be expected. While some of the interviewees were quite willing to provide information about problems encountered with technology, operation, or economic difficulties, the majority of the operators chose to limit their answers. The data collected during interviews and visits were complemented by interviews with suppliers and engineering companies, as well as by analyses of a number of litigated cases. All interviewees identified optimization potential, principally in terms of wear and tear and maintenance, but also relating to their facilities' processing capacities and ability to achieve higher efficiencies. Sedimentation and incrustation in the fermenter and dewatering processes were identified as principle areas for where wear and tear and the need for maintenance could be reduced. Problems with abrasion and corrosion were also reported frequently.

5.3.1 Sedimentation, Flotation, and Incrustation

Problems with sedimentation occur in both wet and dry continuous anaerobic processes. Frequently, sedimentation is accompanied by incrustation, intensifying the solidification of sediments. The effects on operation can be summed up as follows:

- Sedimentation, flotation, and incrustation:
  - Sediments and/or floating of particles in fermenter vessels reduce the available volume. In concrete cases, reductions of up to 40% have been observed.
  - Sediments combined with incrustation can compromise the mechanical equipment in the fermenter, such as mixers and cleaning devices, because they increase mechanical strain or render the whole system inoperable by blockage.
  - In horizontal fermenters with plug-flow technology, sediments can impede the material transport, resulting in shortcuts in material flow. In vertical fermenters, incrustation and blockage of the outlets can occur.
  - Blockage of pipes, various outlets, slide valves and vents, etc.
  - Blockage of fixed beds inhibits the proper flow within the reactor, causing malfunctions in the fixed bed.

- Signs of wear and tear:
  - Excessive signs of wear and tear, which culminate in deterioration, are caused by abrasion and are mainly seen in shredders, pumps, and mechanical dewatering devices.
  - Corrosion is promoted by abrasions.

The abovementioned problems can cause massive operational and economic damage that ranges from reduced performance to total failure of the facility. Fermenters may have to be shut down, opened, evacuated, repaired, and then started up again. When reserve capacities are not sufficiently dimensioned, downtimes of several months can be sustained. Downtimes are also caused by the need for frequent repairs. Further consequences are shorter lifetimes for equipment and components, different warranty periods offered in tenders and costs for maintenance, repair, and operations (MRO). Energy efficiency is compromised by restrictions on the facility's availability.

Approaches

The main approach for wet and dry processes is to minimize minerals and metal fractions prior to feeding the substrate into the fermenter.

Dry processes:

- Efficiently separate Fe and non-Fe metals and other heavy materials and floating particles like plastic and wood prior to feeding the substrate into the fermenter.
- Adjust feedstock viscosity within a narrow range. To minimize sedimentation and flotation, only a narrow viscosity range is available for process control, which does not impair effective pumping and mixing, while still inhibiting, respectively, fast floating particles from sinking too fast. This range has to be determined individually for each facility and feedstock to be processed.
- In order to prevent the formation of potential sedimentation zones, design the fermenter in such a way as to avoid dead zones, especially in vertical fermenters, and to opt for slopes that promote easy sediment discharge. Especially in the outflow area, the substrate needs to be discharged freely in order to purge the sediments from the fermenter and to avoid blockages.
- Depending on fermenter geometry, design suitable flushing and removal devices, if possible. Removal devices, such as push and scraper floors, need to be constructed on appropriate, i.e., abrasion resistant, surfaces, equipped with a sufficient number of hold-down clamps and mounted on stable guide rails. One supplier completely eliminated scraper floors from his portfolio. Sediments can be broken up by installing systems for the injection of pressurized gas or liquids.
- Given that the fermenters have to be opened or emptied, it is recommended to include reserve systems for the fermenters in the technical design to avoid the loss of the anaerobic stage with certainty. An appropriate inoculum is a prerequisite for a brief start-up of the inspected fermenter. However, this approach may not be suitable for smaller facilities due to economic aspects.

- Since maintenance of devices inside the fermenters is usually associated with the opening and emptying of the fermenters, the external assembly of drive systems is favorable.
- The installation of appropriate control systems for the monitoring of sediments and incrustations is recommended. Methods based on acoustic or infrared technology are still being tested and are not yet available as reliable monitoring tools.
- The warranty should define the lifetime of the fermenters until the first inspection or opening, and clarifying liability in case an inspection becomes necessary before the warranty expires.

Wet systems:

The authors possess detailed knowledge of the abovementioned area, resulting from the operation of wet fermenters with or without a fixed bed. The knowledge of fixed-bed reactors stems from residual waste treatment processes:

- Many of the abovementioned solutions are also valid for wet processes, in the same or slightly modified form, and will not be repeated here.
- With fixed-bed reactors (wet process), the solids in the effluent have to be limited to $<1\%$ of the fresh matter. In this way, the aforementioned problems with clogging and blockage of the fixed bed can largely be prevented. Even if incrustations cannot be totally avoided, a considerable part of the basic matrix is removed. With these low solid contents, sludge removal is less expensive, and the formation of floating layers is counteracted.
- The sole separation of heavy materials in the mixer of the pretreatment stage is judged not to be sufficient to counteract sedimentation problems. Generally, good separation results can be obtained with decanter centrifuges. Granular components can usually be removed with sand traps, but are not suitable for the efficient elimination of very fine sands and fibers, which is necessary for fixed-bed reactors. In wet fermenters without fixed beds, a sand trap is often installed after the mixer. Vibrating screens equipped with very fine mesh cloth are appropriate for the almost complete elimination of fibrous substances. However, this equipment is difficult to assess regarding their performance in removing fine sands.

5.3.2 Corrosion and Abrasion

Corrosion, principally of metallic materials, is predominantly observed on peripheral machinery at anaerobic treatment facilities, mostly on the equipment used in the posterior aerobic treatment stage. Damage due to corrosion results in higher expenditures for maintenance and repairs and shorter lifetimes while compromising the process, with the respective effects on operating costs and efficiencies [7]. Unfortunately, composting and anaerobic treatment facilities provide ideal environments for corrosion processes.

Approaches

- Use higher-quality materials for construction and equipment. Stainless steel is recommended for mechanically stressed metal parts, such as those affected by erosion and corrosion by abrasion; do note, however, that corrosion, like pitting, has also been observed in V2A and V4A steels.
- Substitute metal pipes with plastic or mineral-based products. In one case, due to massive corrosion, the replacement of $AlMg_3$ alloy pipes (suction aeration) with plastic pipes became necessary.
- Ensure corrosion protection via suitable coatings. Good experience has been had with three-layered coatings after sandblasting with 80 μm, epoxy zinc dust primer; middle layer, epoxy resin with micaceous Fe oxides; and top layer, polyurethane varnish.
- Improve insulation of process areas at increased corrosion risk from humidity, dust, and organic-rich atmosphere to separate them from other areas of the facility using constructive and process engineering concepts. If possible, relocate sensitive functional components to less corrosive environments.
- Some of the reported corrosion appeared in places damaged during assembly, which had not been sufficiently coated afterwards. These weak points that are never completely avoidable have to be localized and repaired as soon as possible.
- Intensify removal of biofilm deposits from surfaces.
- Establish sufficient air exchange rates in order to better remove warm air and humidity from the composting halls.
- Insulate and operate electric and control cabinets under positive pressure.
- Intensify monitoring of components susceptible to corrosion and protect, as well as immediate replace, damaged anticorrosion coatings.

6 Conclusions

The anaerobic treatment of biowaste and green waste in Germany has not gained the importance it deserves by far, owing to its ecological advantages. This is also evidenced by the high expansion and development potential afforded by the anaerobic treatment. There is a need for action in two areas: (1) increase the amount of biowaste collected by establishing a tightly meshed nationwide expansion of the organic waste bin system and increase the collection rates and (2) channel a large proportion of the biowaste currently only undergoing composting into fermentation as well. The potential for increasing fermentation in Germany is estimated at 5.4 million tons.

Fundamentally, the question must be discussed of whether it is imperative to collect kitchen and garden waste (biowaste) separately or whether it is also possible to sustainably utilize kitchen and garden fractions from mixed waste. Nevertheless, compost from separate collections continues to have significantly better quality than compost from mixed waste. An improvement in the concentrations of relevant heavy metals in compost generated from mixed waste, e.g., by MBT technologies, has been observed since the 1990s. This development is attributable to improvements in reprocessing and conversion technology and to a lower biowaste burden per se triggered by a decline in exhaust emissions. Comprehensive waste analyses are recommended before implementing measures for biowaste utilization that should not only be aimed at determining quantities but also at analyzing the gas potential, for example, and the burden from pollutants. This way, robust data on the sizing of biowaste plants can be provided. In certain regions, like predominantly rural areas, the use of efficient reprocessing and conversion technologies might generate similarly good compost qualities from mixed waste as those produced by complicated separately collected biowaste.

Relevant process technologies have undergone impressive advancements in the past few years. In the 1990s, the construction of wet processes prevailed, whereas almost exclusively dry single-step processes were run in the 2000s. This trend continues at facilities currently under construction. Among the reasons given for this trend in the survey were low investment costs, high operational stability, and user-friendliness. Given the lack of operational experience and sufficiently qualified personnel, the last point is of special importance.

Continuous dry processes have the highest mean net electricity yields. In spite of low intrinsic consumption, dry discontinuous processes do not come close to these yields. Wet processes do not yield higher biogas or methane quantities. Therefore, doubts arise as to whether the comparatively high technological and operational expenditure on the anaerobic treatment of solid waste from mixed waste is justified.

The possibilities for technological optimizations are manifold. In continuous dry processes, the necessity of intensive shredding has to be evaluated in order to find a way to reduce energy demand. In discontinuous processes, better homogenization can result in higher biogas yields. The separation of sedimentable compounds reduces the risk of sediment formation in the fermenter and lessens abrasion or wear and tear in downstream devices – a factor of major importance in the treatment of mixed waste. The formation of floating layers should also be avoided, especially in wet processes.

Thermophilic operations in all processes generate higher yields of biogas (up to 15%) and methane.Most discontinuous dry and wet processes operate within the mesophilic range and therefore hold comparatively high optimization potential. The development of CHP technology has improved electrical efficiency, which can be exploited in new installations and when replacing old units. The available options for gas utilization are currently only applied to a very limited degree. The utilization of process heat still holds an especially high optimization potential.

The dewatering stage ranks as the largest energy consumer. The utilization of surplus heat to control downstream aerobic treatment processes makes material composting with higher water content possible and reduces process water quantities. Positive effects are also expected to prevent wear to dewatering devices, as well as reduce energy consumption. The hygienization of the substrate prior to or during the anaerobic process offers the possibility of direct application onto agricultural fields, at least during the vegetation period. This option holds high optimization potential to increase energy efficiency.

Operational optimization can also be achieved by more regular feeding, including night and weekend shifts where special attention should be given to the management of the stockpiled feedstock. Furthermore, the appropriate maintenance extends equipment lifetimes and saves energy. For example, regular maintenance of the motors reduces the rate of mechanical losses and can yield energy savings of 3%–10%.

The measures described for sedimentation prevention and flotation in the fermenters should be implemented to guarantee a high availability of facilities. Monitoring devices should be installed.

Optimization approaches have been quantified based on the options described for the optimization of energy yields. Such approaches will increase the factors for electricity and thermal energy yields by at least 1.4 and 1.2, respectively [8].

Exploitation of optimization potential will be decisive for increasing efficiencies. Dry discontinuous processes have only been in operation on an industrial scale since 2006. Unlike the continuous processes used on an industrial scale since the mid-1990s, the potential to develop discontinuous processes is estimated to be comparatively high.

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