WP3 – Biogas valorization and efficient energy management

D3.1: Best practices for improved sludge digestion

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

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Abstract	This review covers state-of-the-art technologies for advanced anaerobic digestion of municipal sewage sludge. It is based on an extensive review of literature and available data, focussing on processes which have been realized in full-scale plants. The review includes information on single-stage mesophilic digestion, thermophilic digestion, temperature-phased digestion, high-load digestion and other process modifications, as well as mechanical, thermal, chemical, and biological disintegration methods. All processes are described with a set of key performance indicators such as degradation rate of volatile solids, biogas yield, return load, effects on dewatering, and capital costs.

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Glossary

AD	Anaerobic digestion
CAPEX	Capital expenditures
CHP	Combined heat and power plant
COD	Chemical oxygen demand
CST	Capillary suction time
DS	Dry solids
HRT	Hydraulic retention time
OFMSW	Organic fraction of municipal solid waste
OLR	Organic loading rate
OPEX	Operating expenditures
PE	Population equivalents
PSA	Pressure swing adsorption
MAP	Magnesium ammonium phosphate
SRT	Solids retention time
TPAD	Temperature phased anaerobic digestion
VFA	Volatile fatty acids
VS	Volatile solids
WWT	Wastewater treatment
WWTP	Wastewater treatment plant

Executive summary

This review covers state-of-the-art technologies for advanced anaerobic digestion of municipal sewage sludge. It is based on an extensive review of literature and available data, focussing on processes which have been realized in full-scale plants. The review includes information on single-stage mesophilic digestion, thermophilic digestion, temperature-phased digestion, high-load digestion and other process modifications, as well as mechanical, thermal, chemical, and biological disintegration methods. All processes are described with a set of key performance indicators such as degradation rate of volatile solids, biogas yield, return load, effects on dewatering, and capital costs.

As a benchmark, single-stage mesophilic digestion with 20 days hydraulic retention time (HRT) yields around 420 NL biogas per kg volatile solids (VS) fed for mixed sludge and 300 NL biogas per kg VS_{in} for waste activated sludge under optimium conditions. Related VS reduction rates are around 50% for mixed and 37% for excess sludge.

In general, advanced processes for sludge digestion increase VS reduction and corresponding biogas yield, also typically increasing NH_4-N concentration in the return load. Increasing digestion temperature to thermophilic mode (55°C) or adding a thermophilic first stage in temperature-phased digestion will increase VS reduction and biogas yield by 5-10%, but may have negative impacts on dewaterability. Two stage processes with cascading reactors provide better mixing and control of HRT and also increase degradation by 5-10%, although processes of hydrolysis, acido- and acetogenesis and methanogenesis are not separated here. Separation of these steps can be reached in two-stage processes with a first "acidic" digestion step for hydrolysis and acidogenesis working at pH < 6 and a second step for biogas production, and these systems can reach VS reduction of >60% and related biogas yield. Changing the first digestion step to high-load conditions with higher organic loading rates (> 3 kg VS per m^3 and day) and low HRT can also increase VS degradation and will increase system capacity.

For the sludge disintegration methods, thermal hydrolysis is a reliable method to increase VS reduction, especially for excess sludge. VS reduction of >60% can be usually reached for mixed sludge, but this benefit comes at the cost of higher return load in NH_4-N. A combination of thermal and chemical disintegration at medium temperature (65°C) and high pH seems also promising and may be easier to operate. Mechanical disintegration is energy-intensive and may yield problems in dewaterability, while biological disintegration with enzymes only accelerates VS degradation, but does not enhance it compared to a well-operated conventional system.

Finally, new approaches such as dark fermentation to produce hydrogen are still in the trial phase and have not been tested in full-scale. However, they may form a valuable alternative in the future if they can be established at a larger scale.

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1. Introduction

In general, wastewater treatment plants (WWTP) have been primarily regarded as large energy consumers in the municipal infrastructure. As a consequence of this perspective, attempts to improve energy efficiency of the WWTP with process optimization have mostly been focussed on the reduction of electricity consumption of the water treatment process. However, WWTP can also generate electricity and heat on-site by valorising the biogas from anaerobic digestion (AD) of the sewage sludge in combined heat and power (CHP) plants. Currently, using biogas from digestion of primary and biological (excess) sludge typically leads to a maximum electricity production of 50-70% of the total electricity consumption of the WWTP.

In principle, raw municipal wastewater contains up to 175 kWh per population equivalent (PE) and year of chemical energy potential bound in the organic matter ((Haberkern et al. 2008)). State-of-the-art WWTP with primary sedimentation followed by an activated sludge process currently recover 10%[1] of this energy potential as electricity via AD and subsequent biogas valorization (DWA 2010), equaling around 17 kWh/(PE·a). If this recovery of energy could be increased by more than 80%, the WWTP process will be energy-positive[2] based on the average electricity consumption of a large WWTP of 32 kWh/PE·a (DWA 2013), i.e. producing more electricity than it consumes for treating the wastewater.

This goal of energy-positive WWTP schemes can be reached by following two main approaches: a) to maximize the production of primary sludge with high biogas potential in the WWTP process and b) to maximize the production of biogas in the AD process. While the first approach is followed in WP1 of the POWERSTEP project, this report focusses on the second approach by reviewing existing processes for improved sludge digestion and maximum biogas production in AD of sewage sludge.

Currently, the standard AD process for sewage sludge is a single stage digestion process in mesophilic conditions (35-38°C), usually converting around 45-50% of the organic matter into biogas. However, many different process configurations have been developed and tested in laboratory, pilot, and full-scale to improve the degradation of the organic matter and consequently to increase the biogas production (Carrere et al. 2010).

The goal of this literature review is to:

- Collect information on the different process configurations which have been developed for an improved digestion of sewage sludge
- Evaluate processes with full-scale references using a set of key performance indicators to derive benchmark values for advanced digestion processes and compare them to the current practice (single stage mesophilic digestion).

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[1] Biogas = 18.3 l/d PE, methane content = 65% (=6.5 kWh/m³$_{biogas}$), η_{el} = 40%

[2] Energy-posiitve operation can also be reached by exporting other types of energy carriers from the WWTP, e.g. heat or biogas.

1.1. Process stages of anaerobic digestion

During anaerobic digestion microorganisms break down organic matter in the absence of molecular oxygen. This process can be divided into four stages (Figure 1), where different microbial species use organic products as electron acceptors and thus produce an energy-rich end product (biogas) consisting mainly of methane and carbon dioxide (Rosenwinkel 2015).

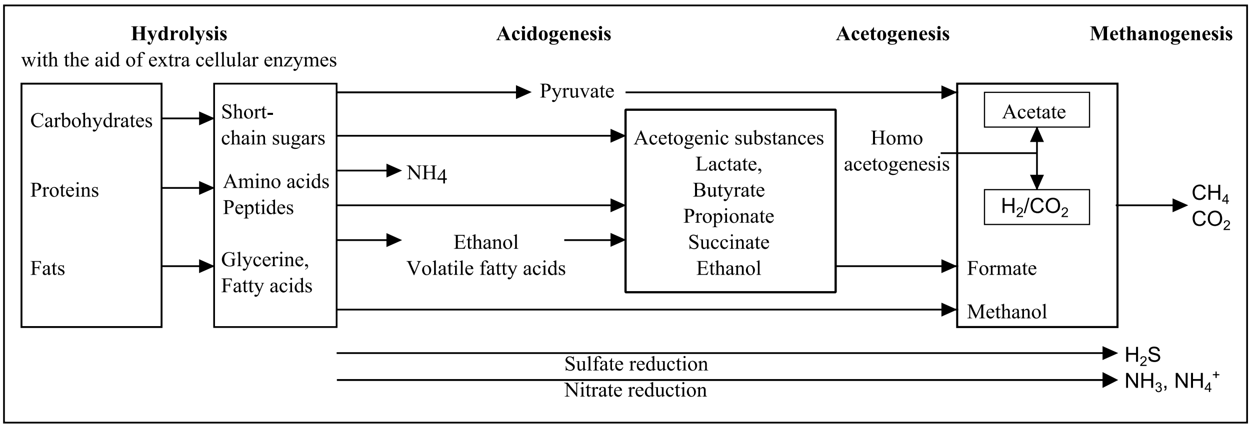

Figure 1: The four stages of anaerobic digestion (Deublein and Steinhauser 2010)

In the first stage of hydrolysis, extracellular enzymes are produced by microorganisms in order to cleave the unsolved biopolymers hydrolytically. Thus, biopolymers become water-soluble and available for acidogenic bacteria. At low hydrogen partial pressure ($pH_2 < 4{,}1 \times 10^{-4}$ bar) acetate, CO_2 and H_2 are the main degradation products of acidogenic bacteria, whereas at higher hydrogen partial pressure ($pH_2 > 4{,}1 \times 10^{-4}$ bar) lactate, propionate and succinate are produced. If these substrates are present, acetogenesis takes place and degrades the long chain fatty acids into acetate, CO_2 and H_2. In the last stage, methanogenics convert either acetate (acetoclastic methanogens) or CO_2 and H_2 (hydrogenotrophic methanogens) into methane and CO_2. Since methanogenic bacteria are substrate specific, it is essential that the previous stages proceed completely (Rosenwinkel 2015).

In state-of-the-art anaerobic reactors, all stages of the AD process take place in one reactor at the same time. Yet, both hydrolytic/acidogenatic bacteria and acetogenetic/methanogenetic bacteria require different environmental conditions to achieve optimal growth rates. Table 1 lists the process parameters under which the respective microorganism group is the most productive. Especially optimum pH value and specific growth rate (which is coupled with hydraulic retention time (HRT) in the reactor) differ between hydrolysis/acidogenesis and acetogenesis/methanogenesis.

Table 1: Environmental requirements for the different stages of AD (Deublein and Steinhauser 2010, Rosenwinkel 2015)

Parameter Example	Hydrolysis/acidogenesis	Methane formation
Temperature	25-35 °C	Mesophilic: 32-42 °C Thermophilic: 50-58 °C
pH value	5.2-6.3	6.7-7.5
C:N ratio	10-45	20-30
DS content	< 40% DS	< 30% DS
Redox potential	+400 to -300 mV	< -250 mV
Required C:N:P:S ratio	500:15:5:3	600:15:5:3
Trace elements	No special requirements	Essential: Ni, Co, Mo, Se
Growth rate	< 2d	2-10d

In single stage digesters, process conditions have to be adjusted according to the requirements of acetogenic/methanogenic bacteria to avoid inhibition by low pH and wash out resulting from a short HRT (Rosenwinkel 2015). Methanogenic bacteria and archaea need either mesophilic or thermophilic conditions (Figure 2), whereas temperatures in between inhibit methanogenic activity. Hydrolysis and acidogenic bacteria are less sensitive towards temperature (Table 1), although higher temperature accelerates hydrolysis.

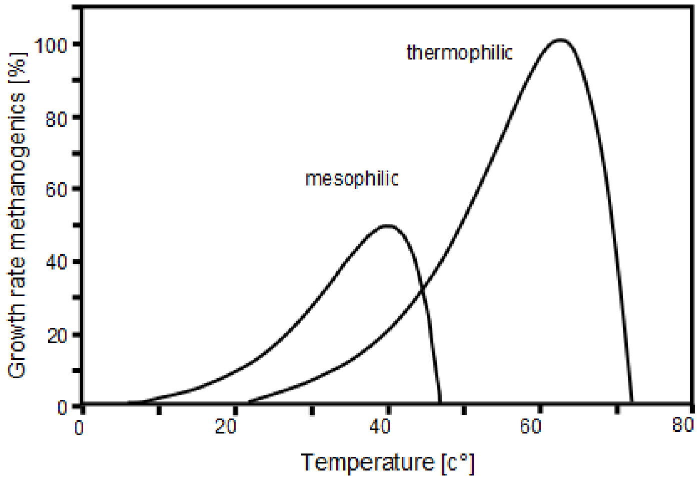

Figure 2: Mesophilic and thermophilic temperature range for methanogenic bacteria and resulting growth rate (Rosenwinkel 2015)

In principle, all advanced AD processes for municipal sewage sludge attempt to enhance or accelerate the hydrolysis stage, as this is generally seen as the rate-limiting step of the entire AD process. Hence, this report will focus on how the hydrolysis rate or extent of degradation can be improved technically by changing either the configuration of process flows and/or the operational parameters of AD.

Adding other co-substrates into the AD process to enhance biogas production ("co-digestion") is not included in this report as a measure to improve biogas production, although it is applied in many WWTPs to use free capacity in the existing AD reactors. However, co-digestion takes its benefits from other substrates (and not wastewater-bound organics) and hence is not directly related to the POWERSTEP concept.

2. Performance indicators

Six performance indicators (a-f) were chosen in order to evaluate and compare the performance of different AD process schemes. Whenever possible, quantitative data for these indicators was obtained from the references analysed in this review. Some references only give qualitative data for selected indicators, which were reported as additional information.

Many studies or reviews of AD evaluate process efficiency on the basis of relative improvement of the digestion performance (Burbaum et al. 2002, DWA 2015). In contrast, performance indicators of this review will primarily present absolute figures obtained from large scale references to derive absolute benchmarks for the different AD processes and to ensure comparability of data from newly built AD units and processes implemented in poor or well performing AD systems.

2.1. Volatile solids (VS) degradation rate

The **relative VS degradation rate in %** measures the progress of AD processes in degrading the content of organic matter in the sludge:

$$VS_{degraded}[\%] = \frac{VS_{influent} - VS_{effluent}}{VS_{influent}} \cdot 100 \qquad \textbf{\textit{(Eq. 1)}}$$

Theoretically, at infinite sludge retention time (SRT) in the AD process, 90 to 95 % of VS is expected to be biodegradable, whereas the remaining 5-10 % is used to build up new biomass (Rosenwinkel 2015). However, SRT is technically limited by reactor size, and thus the AD reaction is not fully completed when the sludge leaves the reactor. In general, the attainable degradation rate depends on the process configuration, the percentage of VS in the raw sludge and the digestion temperature (Rosenwinkel 2015). Typically, the maximum technical VS degradation rate of raw sewage sludge (with VS content of 70 %) is between 65-75 % (Rosenwinkel 2015). Lower VS content in raw sludge results in lower degradation rates in technical AD systems.

2.2. Biogas yield

During the AD process, biogas is produced by the degradation of VS. Hence, biogas yield and VS degradation rate should correlate, as more VS degradation leads to higher biogas yield. The higher the VS load in the feed stream, the more biogas can be generated. To ensure the comparability of AD plants with different influent organic loading rate (OLR), **specific biogas yield is related to the incoming organic load, i.e. measured in Nm^3 biogas per t-VS_{fed}** (Nm^3/t VS_{fed}). Methane content of biogas from AD of sewage sludge is usually between 60-65% due to the stochiometry of the related microbial processes.

In practice, different units (such as mmol-CH_4/g-VS_{fed} or m³/t-DS_{fed}) are used in the literature to express the amount of biogas produced. If no data for unit conversion was provided in the reference, assumptions were made to convert these figures into the basic unit of Nm³/t VS_{fed} (Table 2), using the equation below to convert biogas volumes into normalized conditions.

Table 2: Assumptions for calculation of biogas production (DWA 2010, Rosenwinkel 2015)

Parameter	Unit	
VS in raw sludge	[%]	70 (loss on ignition)
Methane content	[%]	65
System overpressure	[mbar]	25 (mean of non-pressure and low pressure gas storage)
Biogas temperature		Digestion temperature
Density of CH_4	[kg/Nm³]	0.71
Molecular weight CH_4	[g/mol]	16

$$V_N = \frac{V_G \cdot 273}{273 + T} \cdot \frac{P_{atmospheric} + P_{gas}}{1013{,}25} \qquad \textbf{Eq. 2}$$

V_N	Biogas normal volume [Nm³]
V_G	Biogas volume, measured [m³]
T	Biogas temperature [°C]
$P_{atmospheric}$	Atmospheric pressure [mbar]
P_{gas}	System overpressure [mbar]

2.3. Dewaterability

The dewaterability of digested sludge plays an important role in the sludge disposal process, as it has a high impact on the final sludge amount for disposal and thus on disposal costs. In addition, the use of polymer upstream of the dewatering unit is also an important cost factor of the AD process, and any influence of advanced AD on the dewatering performance and polymer consumption should be reported.

The dewaterability of digested sludge can be characterized by different specific values such as final dry solids (DS) in dewatered sludge, loss on ignition, polymer demand, capillary suction time or specific resistance to filtration (Rosenwinkel 2015). In theory a reliable value should not be influenced by variable parameters such as the type of dewatering unit (e.g. centrifuge, belt filter), type of polymer used and specific polymer consumption. However in practice a single specific value cannot fullfill this requirement, as sludge dewatering is a highly site-specific process depending on the actual properties of the sludge (also influenced by seasonal variations) and the optimal combination of dewatering equipment, choice and dosing of polymer, and other process parameters.

As detailed information on the conditions of dewatering are often not available in the literature, it was decided to report the **final DS of digested and dewatered sludge in %** together with the type of dewatering unit (Rosenwinkel 2015). This performance indicator gives a first indication of the effects of advanced AD processes on the dewaterability of the digested sludge. In addition, a relative effect on polymer dosing is reported if available to indicate higher or lower demand for polymer, which is a major cost factor in sludge dewatering.

2.4. Return load (NH_4-N)

During the AD process, several components of the degraded sludge are dissolved into the liquid phase of the sludge, i.e. organic matter measured as chemical oxygen demand (COD), or nutrients such as reduced nitrogen in form of ammonium (NH_4-N). Whereas most of the dissolved COD is converted into biogas, ammonia remains in the liquid phase and is found in high concentrations in the sludge liquor after dewatering. This sludge dewatering effluent (SDE) is usually recycled back to the influent of the WWTP, increasing the nutrient and COD load of the WWTP and causing higher operational costs of ca. 750 €/t N (DWA 2015). Dedicated processes for SDE treatment aim to reduce this “return load” of the mainstream WWTP by removing nitrogen from the SDE prior to recycling.

Advanced AD processes increase both the degradation of the VS and the hydrolysis of compounds into the liquid phase, which often leads to an increase in COD and NH_4-N concentration of the SDE and hence to a higher return load to the WWTP mainstream. However, a higher load in the SDE will increase operating expenses and energy demand of the WWTP mainstream process, especially due to high ammonium loads in SDE which can add between 10-20 % to the total nitrogen load of the WWTP (Rosenwinkel 2015). Hence, **NH_4-N concentration in SDE [mg/l]** is used as a performance indicator to illustrate the effect of advanced AD processes on the return load of the WWTP. SDE of digested sludge can contain 400-1,200 mg NH_4-N/l, depending on the conditioning agent (Rosenwinkel 2015). Therefore, AD processes will be ranked according to their impact on NH_4-N concentration, i.e. whether they lead to strong (>1,200 mg NH4-N/l), medium (800 - 1,200 mg NH_4-N/l) or low (<800 mg NH_4-N/l) effects on the return load. Very high concentrations of NH_4-N (> 1500 mg/l) may lead to inhibitory effects on the digestion process, especially in higher pH when more NH_3 is present.

2.5. Energy Consumption

Advanced AD processes also consume energy in form of electricity and heat for the operation of AD reactors or other treatment steps (e.g. mixing, pumping, heating of sludge). Energy consumption has an impact on process cost and on the net energy balance of the AD process, off-setting some benefits of increased biogas production with energy needed for the sludge treatment. Energy demand of the different advanced AD processes is compared by reporting **gross energy consumption of the processes in heat and electricity related to input volume of sludge**, measured in $kWh_{heat}/m^3_{sludge\ treated}$ and $kWh_{el.}/m^3_{sludge\ treated}$.

2.6. Capital and operating expenditures

Capital expenditures include all incurring capital costs for the installation of the advanced AD process, i.e. either construction of a new biogas plant and CHP unit, the reconstruction of an existing plant or the installation of sludge treatment devices. It has to be noted that capital expenditures depend very much on the existing installations on the specific site, the total size of the WWTP, and other local conditions, which have to be taken into account when comparing information from different references. However, they provide a first estimate of the magnitude of capital investment related to the specific AD process. In this study, the **capital expenditures are measured in Euro per population equivalent** (€/PE) in order to enable a comparison between WWTPs of different sizes.

Operating expenditures involve additional costs for electricity and heat, maintenance, personnel and for operating supplies incurring due to the advanced AD process. Since these costs depend on regional specific variables such as electricity prices, wages or sludge disposal costs, operating expenditures are not listed as a performance indicator in Table 19. Instead they are included in the process description whenever additional operating costs were reported in the literature.

3. Description and evaluation of technologies

The advanced AD technologies/operating methods reviewed in this report can be seperated by:

- operating temperature (i.e. mesophilic and/or thermophilic)
- number of process stages (i.e. single stage, two stages, multiple stages)
- organic loading rate (i.e. high or low)
- addition of pre- or posttreatment of the sludge (e.g. disintegration methods, aerobic post stabilization)

Furthermore, AD systems can be based on dispersed growth in a liquid and attached growth. However, reactors with attached growth are typically relevant for substrates were methanogenesis is the rate limiting step, and thus not applicable for anaerobic digestion of municipal sewage sludge. Hence, the present report focuses on reactors with dispersed growth.

3.1. Single stage mesophilic digestion

Currently it is common practice to digest excess and (if available) primary sewage sludge in covered, continuously stirred, mesophilic reactors at 30 °C – 42 °C (Figure 2). They are usually egg-shaped, as this shape inhibits formation of sediments and the relatively small surface helps to destroy or scrape off floating sludge (Rosenwinkel 2015). However, cylindrical and conical reactors are also in operation.

Under mesophilic conditions the anaerobic process is very stable (compared to thermophilic conditions) and can buffer fluctuation in temperature and feed composition. This is caused by the composition of the microbial community. In mesophilic reactors a variety of microorganisms can be found, whereas in thermophilic reactors key populations can be identified which dominate the microbial community (Pervin et al. 2013).

State-of-the-art mesophilic digesters can be regarded as completely mixed systems in which HRT equals SRT. To produce a biologically stable sludge without major potential of additional gas production, an HRT of 20 d minimum is recommended. However, references show that many state-of-the-art plants have HRT of 30 d and longer (Ros and Zupancic 2004, Mergelmeyer and Kolisch 2014). OLR is usually about 1.5 kg-VS/(m³·d) with a maximum of 2.0 – 3.5 kg-VS/(m³·d) (Rosenwinkel 2015). The reference data in Table 3 was derived from literature and German Water Association guidelines (DWA 2003).

Table 3: Mesophilic single stage digestion (mixed sludge)

Performance indicators						References
Degradation rate *[%-VS$_{degraded}$]*	Biogas yield *[Nm^3/t-VS$_{fed}$]*	Dewaterability *[%-DS]*	Return load (NH_4-N) *[-]*	Energy consumption *[kWh/m$^3_{sludge}$]*	Capital Expenditure *[€/PE]*	
30-50 (Abelleira-Pereira et al. 2015)	400-500	20-30 (belt filter press) 20-32 (centrifuge) 28-40 (chamber filter press)	Low	0.04 kWh$_{el}$ and 0.5 kWh-$_{heat}$ per kg-VS$_{fed}$	107 €/PE (10.000-25.000 PE, new construction of AD unit + CHP+ primary clarifier (BLU 2015))	(DWA 2003) (Rosenwinkel 2015) (Carrere et al. 2010)

To improve efficiency of mesophilic digestion, elevating temperature up to 42°C was tested in pilot trials during summer time by surplus heat of the CHP (Rossol et al. 2005). Results showed a slight increase in biogas production and VS-degradation rate, but the dewaterability declined at increasing polymer demand (+30%). Despite higher energy production, treatment at higher temperature during summer turned out to be economically not efficient (at current sludge disposal costs).

3.2. Single stage thermophilic digestion

Thermophilic digestion temperature ranges between 50 °C and 65 °C (Figure 2), with highest activity at approximatly 60 °C. Because of the more narrow temprature range and lower species variety, thermophilic AD is less stable than mesophilic AD (Rosenwinkel 2015).

Yet microoganism activity is enhanced by higher digestion temperature resulting in shorter HRT (15-25 d) (Willis and Schafer 2006) and better performance of the digester. That leads to higher VS degradation and deactivation of pathogenic microorganisms, which allows the agricultural use of the sludge ("Class A biosolids"). However, thermophilic operation also leads to higher release of NH_4-N (= increased return load) and lower dewaterability (Song et al. 2004).

Table 4: Thermophilic single stage digestion at 55 ˚C

Performance indicators						References
Degradation rate $[\%\text{-}VS_{degraded}]$	Biogas yield $[Nm^3/t\text{-}VS_{fed}]$	Dewaterability [%-DS]	Return load $(NH_4\text{-}N)$ [-]	Energy consumption $[kWh/m^3_{sludge}]$	Capital Expenditure [€/PE]	
42-62	460	CST 30 sec l/g	medium	0.03 kWh_{el} and 1 kWh_{heat} per kg-VS_{fed} (Carrere et al. 2010)	Lab-scale studies	(Lu et al. 2008), (Braguglia et al. 2014), (Kjerstadius et al. 2013), (Wang et al. 2014)
52.7	500	>25 (centrifuge)	High (1,400 mg/l)			(Dichtl and Klinksieg 2004)

Thermophilic single stage digestion of municipal sewage sludge is not often practiced in Europe because of the higher heat demand and potential process instability. However, thermophilic digestion is applied in large-scale at WWTP Braunschweig-Steinhof since 2003 (Dichtl and Klinksieg 2004). Data collected a few months after the shift to thermophilic conditions and an HRT are included in Table 4. They confirm results from laboratory tests (15-20 d HRT) and range at the maximum of standard mesophilic digestion.

3.3. Two-stage mesophilic digestion

Some WWTPs also apply a two-stage configuration for mesophilic digestion. Two different approaches have to be separated here:

- Two-stage systems with two digesters in series, where both reactors are operated in the same conditions (“cascading digestion”) with equal HRT.
- Two-stage systems with two digesters in series, where reactors have different operational conditions to separate processes for hydrolysis and acidogenesis in the first digestor and acetogenesis and methanogenesis in the second reactor. (“two-stage digestion”).

Cascading reactors have been applied in full-scale in WWTPs, and increase of VS degradation from 44% to 49% has been reported (Remy 2012). Total HRT of the cascading system is comparable to single-stage digestors. Positive effects of the cascading configuration may be associated with better mixing and more precise control of the HRT, preventing short-circuiting of sludge due to inefficient mixing. However, more full-scale data of cascading AD systems is needed to precisely quantify the benefits of cascading AD systems over single-stage reactors.

For real two-stage digestion, the primary digester is typically heated to optimize performance of hydrolysis and acidogenic bacteria (T = 32-40°C), whereas the second digester is not heated due to the exothermic nature of methanogenesis (EPA 2006). Due to optimum conditions for the particular steps of AD and thus higher reaction rates, two-stage systems can be operated at higher OLR (4.8-6.4 kg $VS/m^3\cdot d$) and shorter total HRT

(14-18d) than single-stage systems. Naturally, hydrolysis and acidogenesis lead to a lower pH in the first "acid" digester (typically pH < 6), which prevents foaming problems (EPA 2006).

Table 5: Cascading or two-stage mesophilic digestion (mixed sludge)

Performance indicators						**References**
Degradation rate	Biogas yield	Dewater-ability	Return load (NH_4-N)	Energy con-sumption	Capital Expenditure	
[%-$VS_{degraded}$]	*[Nm^3/t-VS_{fed}]*	*[%-DS]*	*[-]*	*[kWh/m^3_{sludge}]*	*[€/PE]*	
49	450	27 (centri-fuge)	High (1254 mg/l)	4 kWh_{el} and 20 kWh_{heat}/m^3	Recon-struction of single-stage di-gestors into cascade	(Remy 2012)
60-65	540-585					(EPA 2006)

3.4. High load digestion

Operating AD systems with a higher OLR is an AD mode called "high load digestion". A dedicatd process for high-load digestion was developed in Germany and later modified by Fraunhofer IGB (Kempter-Regel et al. 2003). The IGB process originates from the Schwarting-Uhde-process which was already patented in 1979 and consisted of two reactors operating at different temperatures (temperature-phased mode, for details see chapter 3.5). The definition of high load digestion for this report is based on the modified Schwarting-Uhde-process by Fraunhofer IGB, which means it refers to all processes with high OLR (>3 kg-VS/m³·d), either by operating two reactors at the same temperature (mesophilic) and different HRT or by decoupling HRT and solids retention time (SRT) through microfiltration in a single-stage process (Kempter-Regel et al. 2003, Kempter-Regel 2010).

In principle, higher OLR increases the technical maximum for VS degradation (Rosenwinkel 2015) and thus leads to higher biogas production. In addition, shorter HRT allows for smaller digester volumes, which decreases the footprint of the process. But more complex AD systems with either two reactors or microfiltration cause higher investment costs and also higher efforts for operation and maintenance.

3.4.1. High load digestion (two reactors, different HRT)

Figure 3 shows a schematic diagram of the high load digestion in Heidelberg (Weber et al. 2002, Kempter-Regel et al. 2003), representing the two stage version. The two existing digesters (D1 and D2) were extended by two preceding smaller digesters (HD1 and HD2) to increase capacity and to reduce foaming problems.

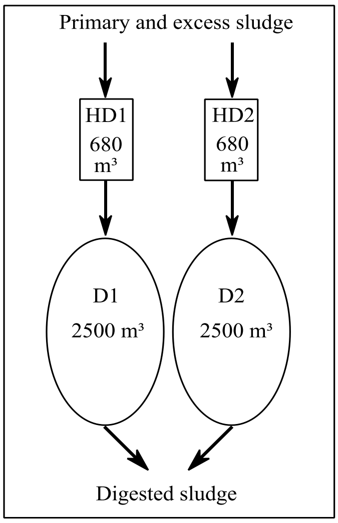

Figure 3: High load digestion by Fraunhofer, two reactors at same temperature (Kempter-Regel et al. 2003)

The first stage is fed with pre-thickened mixed sludge and has an OLR of 8-10 kg VS/(m^3·d) and a HRT of 5 d. Since the old digesters in the second stage were integrated into the new system, their OLR and HRT are predetermined by their volume and thus have lower OLR and higher HRT than necessary (Kempter-Regel et al. 2003).

3.4.2. High load digestion with microfiltration

Figure 4 shows a single stage digester, were microfiltration is used to increase OLR up to 4-6 kg/(m^3·d) by decoupling HRT and SRT. This modification is especially relevant for small plants were hydraulic loading rate substantially exceeds solids loading rate (Kempter-Regel 2010).

During the recirculation process, sludge water is drawn off from the digester and thickened by a rotating disc filter. To minimize operating problems, attention should be paid to the filtration method. Cross flow filtration should be preferred over dead end filtration to prevent formation of a sludge cake. Additionally the filter material must be chosen carefully to avoid clogging and membrane fouling. At WWTP Schozachtal (Nachtigall 2012) for example the microfiltration is made of sintered ceramic, has an average pore space of 0.2 µm and rotates at 320 rpm a filtration method which prevents formation of a sludge cake. The filtration unit has to be cleaned at least once a year.

Permeate contains high concentrations of dissolved ammonium and phosphate which could be recovered by further treatment whereas retentate is redirected to the digester.

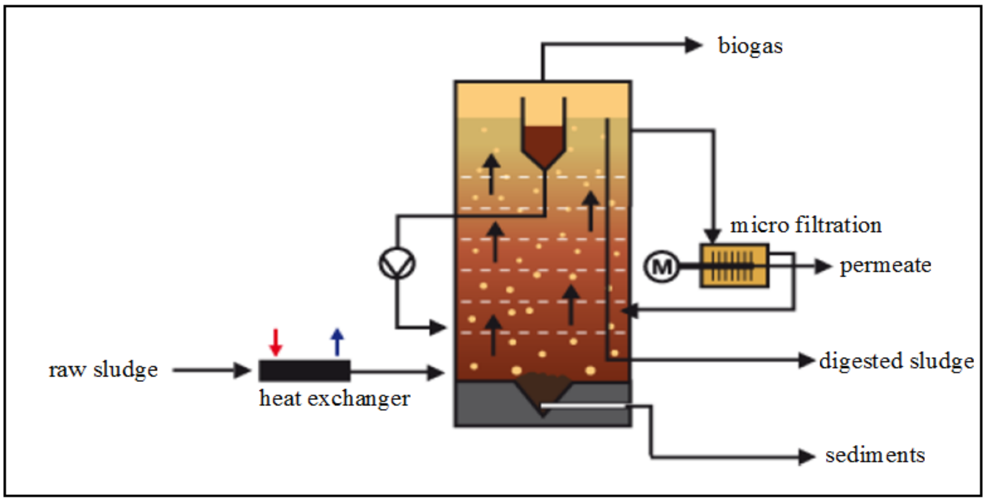

Figure 4 - High load digestion with microfiltration (Kempter-Regel 2010)

Performance results of two large-scale high load AD plants are summarized in Table 6 and Table 7. The two stage version obtains biogas yields and degradation rates above mesophilic single stage maximum, whereas performance indicators of high load single stage digestion with microfiltration are within the range of the minimum of mesophilic single stage digestion. But the more comprehensive analysis in Figure 12 shows that considering the HRT (HRT = 7 d and SRT = 8.6 d), biogas yield in the plant with microfiltration ranges at the maximum of mesophilic single stage as well. Capital expenditures for expanding the WWTP with a two-stage high load digestion do not differ significantly from expanding it with a single stage mesophilic digestion. Comparing electricity demand of microfiltration process and single stage mesophilic digestion shows that high load digestion with microfiltration requires approximately 10-times more electrical energy.[3]

Instead of using microfiltration, a centrifuge can also be used to decouple HRT and SRT. (Berg et al. 2016) studied the effect of dewatering and thickening part of the digested sludge by a decanter centrifuge with polymer dosing. The gas yield obtained was slightly higher than in the control test with a single stage mesophilic reactor, but polymer demand in the final dewatering almost doubled. Authors suggest this was caused by treatment of 50 % of the sludge with polymer already once before final dewatering.

Table 6: High load digestion two stages (mixed sludge)

Performance indicators						References
Degradation rate	Biogas yield	Dewaterability	Return load ($NH_4.N$)	Energy consumption	Capital Expenditure	
[%-$VS_{degraded}$]	[Nm^3/t-VS_{fed}]	[%-DS]	[-]	[kWh/m^3_{sludge}]	[€/PE]	
60	559	27-28 (+ lower polymer de-				(Weber et al. 2002, Kempter-Regel et al. 2003)

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[3] Assuming that 1 m³ of raw sludge digested in a single stage mesophilic reactor contains 10 kg-VS/m³.

		mand)				

Table 7: High load digestion single stage with microfiltration (mixed sludge)

Performance indicators						References
Degradation rate	Biogas yield	Dewaterability	Return load (NH_4-N)	Energy consumption	Capital Expenditure	
[%-$VS_{degraded}$]	[Nm^3/t-VS_{fed}]	[%-DS]	[-]	[kWh/m^3_{sludge}]	[€/PE]	
40	411	30 (belt filter press)	Medium (1200 mg/l)	4,83 kWh_{el}/m^3 (microfiltration + AD)	103 (new construction of AD unit + CHP+ primary clarifier, two stage high load (Hydro-Ingenieure 2013, Ministerium für Umwelt 2014))	(Kempter-Regel 2010, Nachtigall 2012)

3.5. Temperature phased anaerobic digestion

Temperature phased anaerobic digestion (TPAD) is a multiple stage process in which the sludge is treated in two or more digesters at different temperatures. The purpose of TPAD is to achieve higher OLRs and lower HRT by separation of hydrolysis/acidogenesis and acetogenesis/methanogenesis. While reactions and microbial activity for hydrolysis and acidogenesis are faster with high temperatures, acetogenesis has an optimum temperature range of 38-40°C and can be adversely affected by higher temperatures (EPA 2006).

By adjusting the process parameters according to the needs of acidogenic and acetogenic/methanogenic microorganisms (Table 1), hydrolysis and acidification of the biopolymers are supposed to take place in the first and methane formation in the second reactor. However, due to the heterogenic and variable constitution of municipal sewage sludge it is difficult to realize separation of stages in large scale processes, and methane is usually produced in both stages (Willis and Schafer 2006).

Laboratory studies examined TPAD of primary sludge and of excess sludge, respectively (Ge et al. 2010, Ge et al. 2011). They found that methanogenic activity in the first stage at thermophilic temperature (50-65°C, HRT in the first stage = 2 d) occur when excess sludge is present. TPAD of primary sludge in the same experimental set up showed no methanogenic activity in the first stage[4]. The authors concluded that for excess sludge

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[4] [Ge, Jensen et al. (2011)] explain that under thermophilic conditions syntrophic acetat oxidation by methanogenic microorganisms is enhanced. Syntrophic acetat oxidation only takes place when hydrogen partial pressure is low [Rosenwinkel (2014), S. 35]. Since hydrogen production from proteins (proteins account for about 61% of ES and 18% of PS) is much lower than from carbohydrates (carbohydrates account for about 11% of ES and 45% of PS) [Rosen et al. (2006)], syntrophic acetat oxidation appears only when excess sludge concentration is high. Hydrogenotrophic methanogens which life in syntrophic association with acetat oxidizing bacteria have a low doubling time (6-18 h [Belsgen (2009), S.17], which is why low HRT is insufficient to separate stages when excess sludge is present.

a short HRT in the first digester is not sufficient and either a temperature of > 65 °C or a pH=5 is needed to inhibit methanogenesis (Ge et al. 2010, Ge et al. 2011).

TPAD systems can operate at elevated OLRs from 3 to 6 kg-VS/m³. Sequencing of temperature phases can be either thermophilic (or hyper thermophilic[5]) – mesophilic, hyper thermophilic – thermophilic or mesophilic – thermophilic, while the latter resembles a "cascading" two-stage design combined with different temperature levels. Besides VS reduction, TPAD aims at increasing biogas production and removing pathogens through improved biodegradation due to higher temperatures (Carrere et al. 2010). Even though TPAD enhances intrinsic bioactivity and thus biodegradation, non-biodegradable organic substances remain in the sludge.

The technique combines benefits of mesophilic and thermophilic digestion, i.e. it is a stable process with higher degradation rates and the capability of absorbing shock loads (Song et al. 2004). In addition, when HRT in the first stage is kept shorter than in the second stage, which is usually the case, it profits from the same advantages as high load digestion.

3.5.1. Thermophilic – mesophilic sequencing

SRT can be decreased by up to 50 % by thermophilic – mesophilic TPAD (Rosenwinkel 2015). HRT examined in laboratory tests for the first stage varies from 1-7 days and is much shorter than HRT in the second stage which usually is 10-20 days. However in large scale applications (e.g. (Krugel et al. 2006)) HRT can be the same in both stages to ensure operating reliability, e.g. for parallel operation in case of maintenance work. If disinfection is intended, a minimum SRT of 2 h in the first thermophilic stage without any contact to untreated raw sludge is required. An appropriate feeding procedure has to be applied accordingly (Rosenwinkel 2015).

Operating temperature in the first stage varies from 55°C to 70°C. Lab studies observed that increasing the temperature in the first stage from 50 °C to 65 °C did not lead to higher VS destruction rate or higher methane production (Ge et al. 2010). Therefore the first stage should be either operated at 55 °C (thermophilic optimum) or at 70 °C if further elimination of pathogens is required. Generally biogas production can be increased by implementing a preceding thermophilic stage, but results showed no consistency (Carrere et al. 2010).

Despite tested in laboratory abundantly, TPAD with thermophilic-mesophilic sequencing is not common in Europe. In 1997, 10 plants were reported in Germany using TPAD of which only 5 had high efficiency (Torres and Bandala 2014). As there is no evidence whether the five TPAD plants are still in operation, they were not considered in Table 8.

More recently a plant in Norway combined TPAD and thermal hydrolysis (CAMBI), and the achieved results are included in Table 8 (Panter et al. 2006). In the USA TPAD is applied more often (Sieger and Brady 2004) but data availability is low and only one study was found (Krugel et al. 2006). Even though only excess sludge is treated in the US plant,

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[5] Hyper thermophilic: only few bacteria are known, most of them belong to archaea. Their optimal growth temperature is above 80 °C and the maximum is 113 °C. (Thermophiles: Biology and Technology at High Temperatures, p. 99, Robb, Frank, 2008)

the obtained results are similar to those of state-of-the-art single stage mesophilic digestion of mixed sludge, which shows the positive impact of TPAD on VS degradation.

Table 8: TPAD (thermophilic-mesophilic)

Performance indicators						References
Degradation rate	Biogas yield	Dewaterability	Return load (NH_4-N)	Energy consumption	Capital Expenditure	
[%-$VS_{degraded}$]	*[Nm^3/t-VS_{fed}]*	*[%-DS]*	*[-]*	*[kWh/m^3_{sludge}]*	*[€/PE]*	
45	454	27 (by centrifuge)	medium (800 mg/l) (Dichtl and Klinksieg 2004)	0.04 kWh_{el} and 0.5 kWh_{heat} per kg-VS_{fed} (Carrere et al. 2010)		(Krugel et al. 2006)
>60	624					(Panter et al. 2006): TPAD + CAMBI

Operating problems of TPAD such as MAP precipitation in the heat exchanger, NH_4 inhibition and low process stability/foaming might occur during thermophilic-mesophilic operation. In WWTP Braunschweig, they caused a change in process from TPAD operation (first digestor: 53°C, 9 kg oTR/m³*d, HRT = 4d, pH = 6.8-7.2) back to single stage thermophilic digestion (Dichtl and Klinksieg 2004).

3.5.2. Mesophilic – thermophilic sequencing

Mesophilic – thermophilic sequencing in TPAD is not as common as the sequencing of thermophilic-mesophilic described above. It does not aim on separating acidogenesis and methanogenesis and uses equal HRT and comparable pH in both stages, resembling a "cascading" two-stage design. This type of configuration can prevent the development of extremely odorous gases, typically resulting from high VFA concentration and low pH in the first stage at thermophilic temperature (Willis and Schafer 2006). The sludge is hygienized at 55°C in the second stage. The principle of mesophilic – thermophilic sequencing is applied in the patented Schwarting-Uhde-Process which is used at several WWTP in Germany, e.g. WWTP in Leonberg/Germany (Merz et al. 1999). This process uses a high-load first stage at mesophilic temperature (normal pH) and a second digestion stage at thermophilic temperature (= cascading design). The mass balance of the Schwarting-Uhde-process (Figure 5) illustrates its benefits, namely lower sludge production, higher biogas yield and increased net energy production at the cost of higher energy demand. It has to be noted that dewatering in the reference case is specifically low (20% DS) compared to the state-of-the art in dewatering operation (>25% with standard mesophilic digestion).

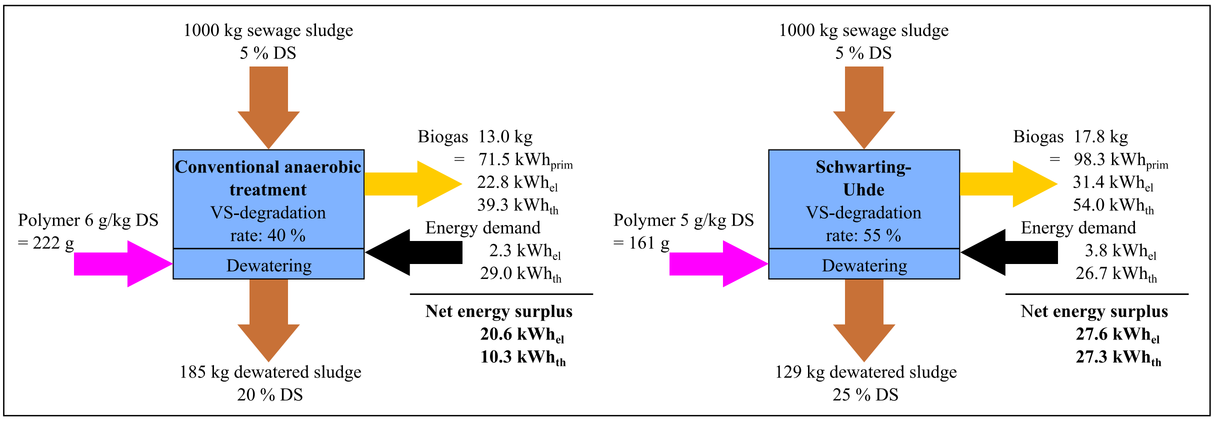

Figure 5: Mass and energy balance of single stage mesophilic digestion (low dewaterability assumed) and Schwarting-Uhde-process (Thomé-Kozmiensky 1998)

Performance of mesophilic-thermophilic TPAD in WWTP Leonberg (Table 9) confirms the mass balance calculation. At an HRT of app. 5-7 days in each stage it achieves better results in VS reduction and biogas yield than mesophilic single stage maximum.

Table 9: TPAD (mesophilic-thermophilic, mixed sludge)

Performance Indicators						References
Degradation rate	Biogas yield	Dewaterability	Return load (NH_4-N)	Energy consumption	Capital Expenditure	
[%-$VS_{degraded}$]	[Nm^3/t-VS_{fed}]	[%-DS]	[-]	[kWh/m^3_{sludge}]	[€/PE]	
54	591	32 (no info on dewatering device)		3.57 kWh_{el}/m^3 28.6 kWh_{heat}/m^3	75 €/PE (new construction of AD unit + CHP)	(Merz et al. 1999)

3.6. Disintegration

Disintegration of sludge for anaerobic digestion can either be applied as a pre-treatment step (usually for excess sludge) or as intermediate treatment for the digested sludge. Intermediate disintegration of the sludge has mainly two advantages: a) the treatment volume is reduced by the degradation in the first digester and b) disintegration is directly applied to the less bioavailable fraction.

The objective of disintegration is to destroy the sludge floc structure and at higher energy input to dissolve cell walls. The effect can be measured by the degree of disintegration which is determined by the COD released or solubilized compared to the initial COD (Müller 1996).

Through disintegration, non-biodegradable organic substances become bioavailable, causing higher VS-degradation rates and an increased biogas yield. Disintegration methods are classified according to their active principle which can be physical, chemical or biological (figure 5).

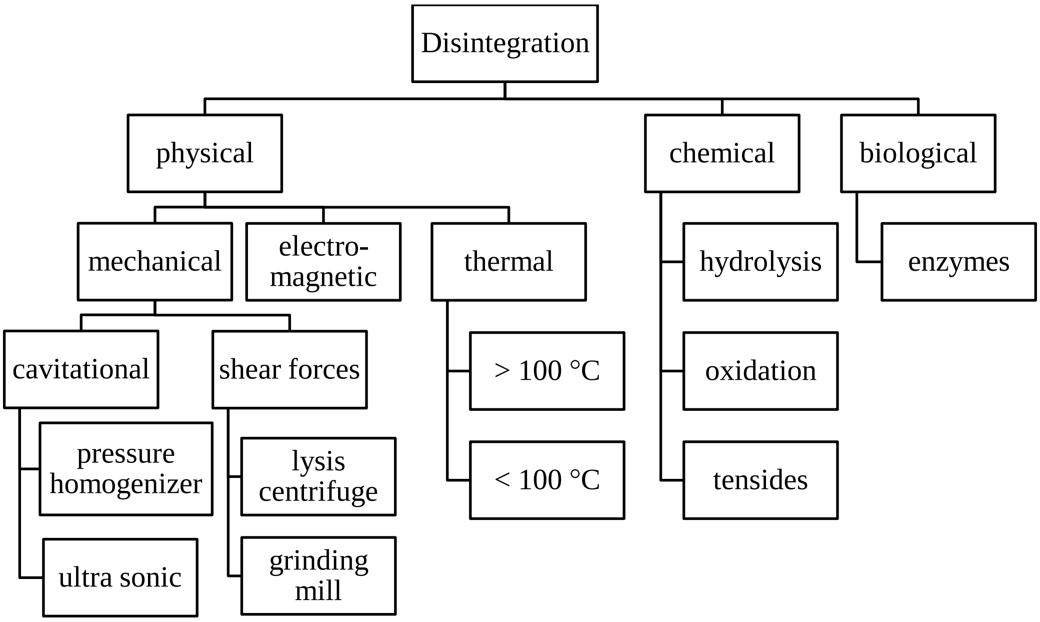

Figure 6: Disintegration methods classified by active principle (DWA 2015)

If disintegration is applied at plants with long HRT in the AD (30-40 d) and a high VS-degradation rate, only a small increase in biogas production will be observed, as the additional effect of disintegration is rather small. If applied at a plant with high loading rates and low HRT (15 d), a significant increase in biogas yield and VS-degradation rate can be expected with disintegration (Schmelz and Müller 2004).

3.6.1. Mechanical disintegration

Pressure homogenizer

During this process sludge is pumped through a narrow valve (1 mm) with high pressure and high velocity (Roxburgh et al. 2006). Sludge flocs and cell walls are disrupted by a combination of large pressure drop, turbulent eddies and strong shearing forces. The most important variable is the homogenization pressure which is usually around several 100 bar. Studies show that microbial cell disruption is more efficient when higher homogenization pressure is applied instead of multiple homogenization cycles.

Since larger particles can cause blocking of the valve, the sludge has to be pretreated in a pressure screen. Still the valves are wearing parts and have to be replaced occasionally (DWA 2015).

The results in Table 10 were obtained from tests (pressure homogenization at 150 bar) at two large scale plants (Sievers et al. 2006). Both plants performed above single stage mesophilic maximum, and higher biogas yield and VS-degradation rate of one plant can be explained by longer HRT, a two staged process and a higher ratio of primary to excess sludge volume. The study showed that pressure homogenization of digested sludge was more efficient than pressure homogenization of the excess sludge. Therefore authors recommend applying pressure homogenization as an intermediate disintegration step for digested sludge. The NH_4-N load from the return flow did not increase significantly which indicates that pressure homogenization at 150 bar causes rather floc destruction than cell disruption.

Table 10: Pressure homogenizer (mixed sludge)

Performance Indicators						References
Degradation rate [%-$VS_{degraded}$]	Biogas yield [$Nm^3/t\text{-}VS_{fed}$]	Dewaterability [%-DS]	Return load (NH_4-N) [-]	Energy consumption [kWh/m^3_{sludge}]	Capital Expenditure [€/PE]	
57-64	478-541	41.9 (chamber filter press, stable polymer demand of 6 kg/t-DS)	Low (671 mg TN/l)	5,5 kWh_{el}/m^3 sludge treated (DWA 2015)	2 €/PE (pressure homogenizer + installation)	(Sievers et al. 2006)
58.1	550	18 (belt filter press)	Low (472 mg/l)		0.41 €/PE (pressure homogenizer)	(Rabinowitz and Stephenson 2006)

The patented MicroSludge™ (Rabinowitz and Stephenson 2006) combines pressure homogenization with chemical treatment. First waste activated sludge is macerated and/or pH is increased by alkali treatment (e.g. with sodium hydroxide) then pressure homogenization is applied. The alkaline agent helps to solubilize cell wall lipids and thereby makes the cells more prone to disintegration (Stephenson and Dhaliwal 2000). The method is mainly applied to pre-treat excess sludge to increase overall digestability and dewatering characteristics.

Results for treatment of excess sludge with combined treatment (Rabinowitz and Stephenson 2006) and only pressure homogenization (Sievers et al. 2006) are similar. None of them was economically feasible for the plants they were tested at (Sievers et al. 2006, Gary et al. 2007).

Pressure homogenization at lower pressure (< 100 bar) by a simple nozzle causes hydrocavitation. It requires less energy but at the same time disintegration degree is very low, resulting in an insignificant increase in biogas production and degradation degree (DWA 2015).

Ultrasonic treatment

Ultrasonic treatment is especially applied to excess sludge to increase its bioavailability by releasing extra polymeric substances. It is widely implemented at large scale plants. (Ndoh Rossier et al. 2007) reported 32 plants using ultrasound systems from different companies to enhance anaerobic digestion efficiency. During the process, piezoceramic transducers generate a mechanical pulse which is transmitted as high frequent oscillations by sonotrodes into the suspension. The ultrasound waves propagate in the medium by pressure fluctuation causing some spots with positive and others with negative pressure resulting in cavitation (i.e. the formation of vapor cavitites in a liquid). Micro bubbles pulsate by ultrasound resonance, become bigger and eventually implode. Thereby jet streams occur with high shear forces which destroy sludge flocs and at higher frequency disrupt cells. At the same time high temperature (up to 5,000 K) and high pressure (up to 50 MPa) can be found inside the imploding bubbles. (Neis et al. 2008, DWA 2015)

Table 11 shows two full scale plants which are pre-treating part of the excess sludge with ultrasound prior to anaerobic digestion. The ultrasonic unit at the smaller plant (Schmelz and Müller 2004) was in operation for 12 weeks (company Sonotronic Nagel), whereas the bigger plant (Neis et al. 2008) operates its unit since 2004 (Ultrawaves GmbH). It turned out that implementation of ultrasonic pre-treatment at the smaller plant would not be economically feasible. As Table 11 indicates, the specific energy consumption would be eleven times and the capital expenditure seven times higher compared to the bigger plant.

Both plants obtain degradation degrees which are above mesophilic single stage level and a biogas yield at the mesophilic single stage maximum. The tests at the small plant confirmed that dewaterability decreases despite rising polymer demand and that NH_4-N load of the return flow increases due to ultrasonic pre-treatment. Even though the NH_4-N contamination in the larger plant seems to be relatively low, it should be considered that only 30% of the excess sludge was treated with ultrasound.

The ultrasound unit is rather insensitive to impurities and low in maintenance costs, only the sonotrodes have to be replaced from time to time.

Table 11: Ultrasonic treatment (mixed sludge)

Performance Indicators						References
Degradation rate	Biogas yield	Dewater-ability	Return load (NH_4-N)	Energy consumption	Capital Expenditure	
[%-$VS_{degraded}$]	*[Nm^3/t-VS_{fed}]*	*[%-DS]*	*[-]*	*[kWh/m^3_{sludge}]*	*[€/PE]*	
53.8-60.4	442-570	Increased polymer demand - 0.5% DS compared to reference test	Low (446 mg/l, +5%)	2.4 kWh_{el}/m^3 ES (for 330,000 PE) and 28.1 kWh_{el}/m^3 ES (for 17,000 PE) for operating US unit	1 €/PE (for 330,000 PE) and 7 €/PE (for 17,000 PE)	(Winter 2003, Schmelz and Müller 2004, Neis et al. 2008, Wolff et al. 2009)

Lysate-centrifuge

Lysate centrifuges are common centrifuges as used for final sludge dewatering but equipped with a disintegrating device. The additional energy needed due to the disintegration device is negligible, especially for high capacity centrifuges (Zábranská et al. 2006). Purpose of the treatment is cell disruption and thereby activation of exo-enzymes (Winter 2003). As a secondary effect, the sludge is thickened and thus the VS loading rate of the digester and retention time increases.

Table 12 summarizes performance data from lysate-centrifuge operation at plants of different size. Even a though a VS-degradation rate above single stage mesophilic maximum is reported, biogas yields range only between average and maximum mesophilic single stage level.

Table 12: Lysate-centrifuge (mixed sludge)

Performance Indicators						References
Degradation rate	Biogas yield	Dewaterability	Return load (NH_4-N)	Energy consumption	Capital Expenditure	
[%-$VS_{degraded}$]	*[Nm^3/t-VS_{fed}]*	*[%-DS]*	*[-]*	*[kWh/m^3_{sludge}]*	*[€/PE]*	
> 60	361-554	31.5	Low (491 mg/l)	11.4 kWh$_{el}$/m^3	1,22 €/PE, reconstruction of existing lysate centrifuge	(Zábranská et al. 2006, Carrere et al. 2010, Jenicek et al. 2013)

(Winter 2003) compared digestion behavior of lysate-centrifuged sludge and untreated reference sludge. In order to obtain the same DS of pretreated and reference sludge and to eliminate the effects caused by thickening, such as higher retention time, the centrifuged sludge was diluted. During the test period biogas production and VS-degradation rate of the pretreated sludge remained below the level of untreated sludge. That explains the results and indicates that the effects rather result from thickening and longer retention time than from cell disruption.

Stirred ball mill

Stirred ball mills are usually cylindrical drums which are either arranged vertically or horizontally. The grinding chamber is filled with grinding balls which are made of glass, ceramic or steal and account for 70 to 90 % of the total volume. Rotation of the ball mill and the resulting movement of the grinding balls cause disintegration of suspended dry solids in the feed stream by shear forces. The suspension is separated from the grinding balls by a screen before it leaves the mill. (DWA 2015)

(Winter 2003) tested a stirred ball mill for 13 weeks on a WWTP with 17,000 PE. Results in Table 13 show that VS-degradation rate and biogas yield above mesophilic maximum were obtained. But an economic feasibility study indicated that the increase in electricity production and the decrease in disposal costs would be insufficient for an economical operation.

Table 13: Stirred ball mill (mixed sludge)

Performance Indicators						References
Degradation rate	Biogas yield	Dewaterability	Return load (NH_4-N)	Energy consumption	Capital Expenditure	
[%-$VS_{degraded}$]	*[Nm^3/t-VS_{fed}]*	*[%-DS]*	*[-]*	*[kWh/m^3_{sludge}]*	*[€/PE]*	
49.5	550	Increased polymer demand (+7.4%) - 2.9 % DS compared to reference test	Low (417 mg/)	21.1 kWh$_{el}$/m^3	19.8 €/PE, stirred bead mill including housing and machinery	(Winter 2003)

Full scale data of continuous operation of a stirred ball mill for disintegration of municipal sewage sludge have not been obtained yet (DWA 2015).

3.6.2. Thermal hydrolysis

Thermal disintegration for hydrolyzation of sludge can be divided into processes using temperatures above 100 °C and below 100°C (DWA 2015).

Lower treatment temperature (50 °C – 70 °C) increase the sludge intrinsic biodegradability by improving enzymatic hydrolysis of lipids, polysaccharides and proteins. Therefore its effect is rather biological than physical (Carrere et al. 2010). As this effect is already described for TPAD, all case studies found on thermal hydrolysis with temperatures <100 °C are considered in chapter 3.5.

Physical effects result from treatment at temperatures above 100 °C and the corresponding over pressure. In addition to the above mentioned effects the more extreme conditions cause the disruption of cell walls and even smaller fractions such as amino acids by physical stress. That leads to an increased concentration of bioavailable material and ammonia (Horn et al. 2009).

Thermal hydrolysis is applied to enhance VS-degradation and thereby to reduce the sludge amount as well as to increase biogas yield and digester capacity. At the same time the dewaterability characteristics should be improved and pathogens should be eliminated. Temperatures above 180°C only increase the hydrolyzation degree slightly but promote the formation of inert substances such as non-biodegradable (“refractory”) COD in the return load, which may cause an increased COD of WWTP effluent. Therefore treatment temperatures below 180 °C are recommended (Horn et al. 2009).

Sludge temperatures above 100 °C can be generated either directly by hot steam injection or indirectly via a heating medium (hot water, thermal oil, heating steam) through a heat exchanger (DWA 2015).

Direct heating by steam injection is applied in the patented CambiTHP™ process developed by CAMBI AS (Figure 7). Pre-thickened sludge (≈ 8-10 % DS) is transferred into a reactor were temperature and pressure are increased by steam injection to about 165 °C and 5-6 bar respectively. After 20-30 min of heating a sudden drop in pressure by opening the flash valve results in “steam explosion” into the flash tank which enhances the disintegration effect by tearing cells and fibers apart.

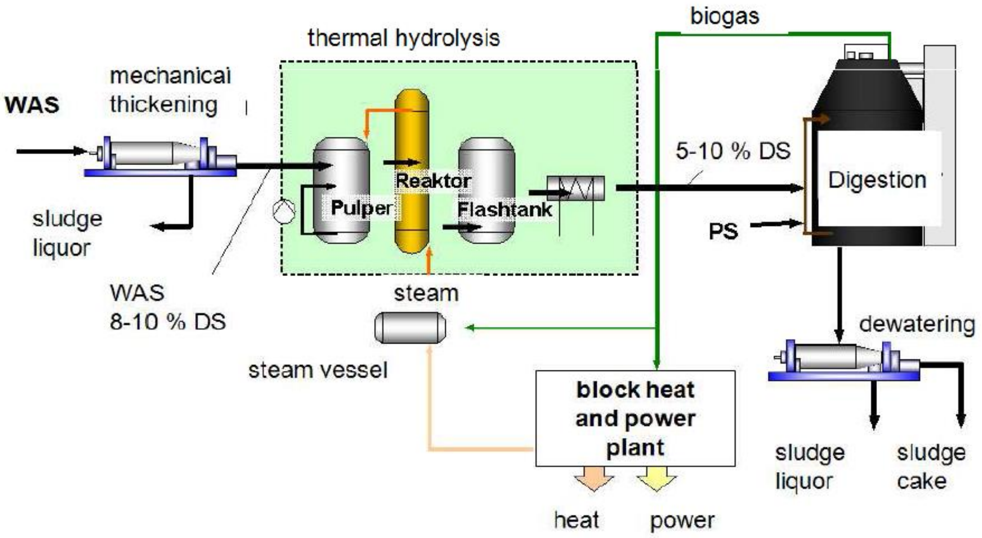

Figure 7: CambiTHP™ process (Kopmann and Kopp 2010)

The TurboTec® process developed by Sustec B.V. (Figure 8) also uses direct heating by steam injection. In this process, the hydrolyzed sludge is cooled in a heat exchanger (to 105 °C) and then mixed with the thickened raw sludge (7-14%) by the patented Mobius mix-separator in order to pre-heat the raw sludge. The mixing unit is able to separate the fluidized hydrolyzed sludge and the thicker raw sludge based on their different viscosity. The thin fraction is diverted directly to the digester, whereas the thicker fraction, containing a mixture of non-hydrolyzed sludge flocs and flocs from the untreated raw sludge, is diverted to the hydrolysis reactor.

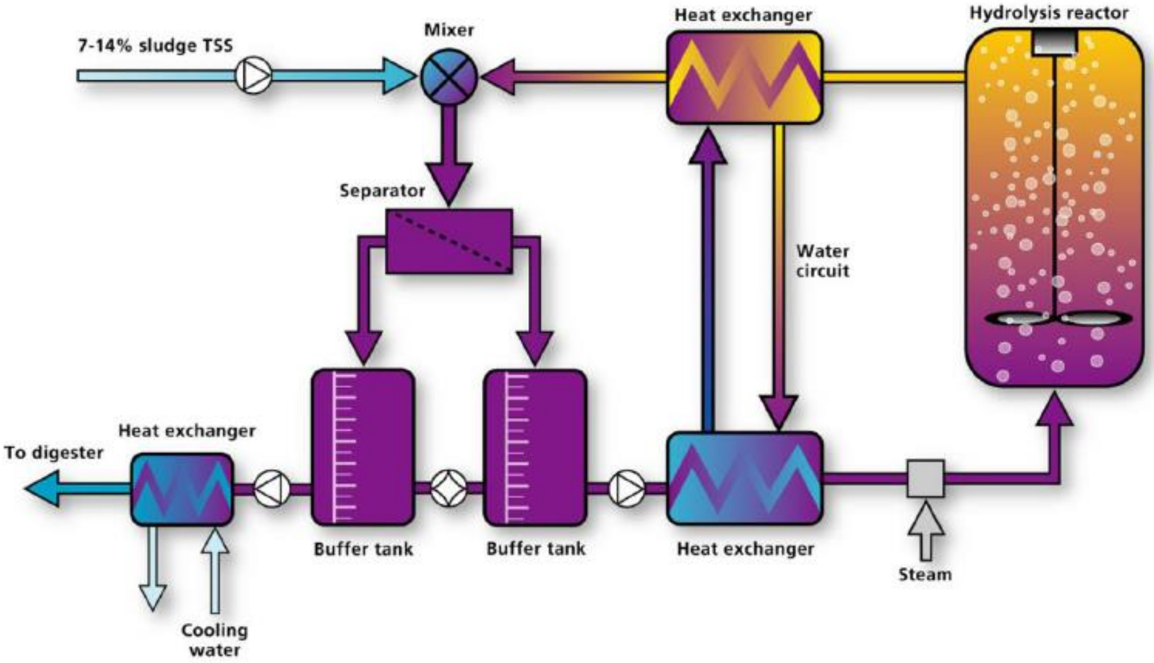

Figure 8: TurboTec® THD process at WWTP Venlo (Boehler et al.)

Direct heating processes which are usually operated in batch mode lead to larger equipment and higher CAPEX and OPEX compared to a continuously operated thermal hydrolysis. The Exelys™ process minimizes these costs and the plants' footprint by continuous operation and by applying thermal hydrolysis to digested sludge prior to another digestion step. Reduction in DS by 35 % during the first digestion step and pre-thickening of the digested sludge to DS = 18-25 % leads to 30 % less energy consumption for thermal hydrolysis. About 2/3 of the biogas is produced in the first digester (Bonkoski 2013).

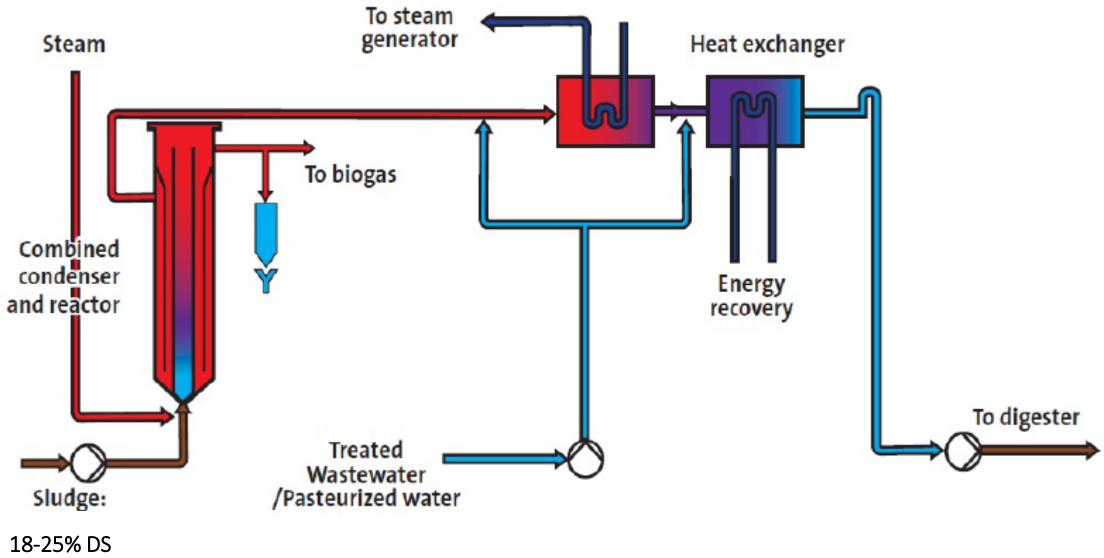

Figure 9: Exelys Process (Bonkoski 2013)

LysoTherm® represents an indirect process to heat the sludge by thermal oil (Figure 10). The pre-thickened excess sludge (6 % DS) is pumped through a heat exchanger system where it is first heated by the hydrolyzed sludge and then in the second stage by thermal oil in a tube reactor. The actual disintegration takes place in the disintegrating reactor at 150 – 175 °C (30-60 min) which usually is designed as a pipe system (DWA 2015), yielding a continuous process.

Because no steam is injected, the sludge is not diluted, resulting in thicker sludge so that digester volume can be reduced. Operating problems might be caused by MAP precipitation in the heat exchangers.

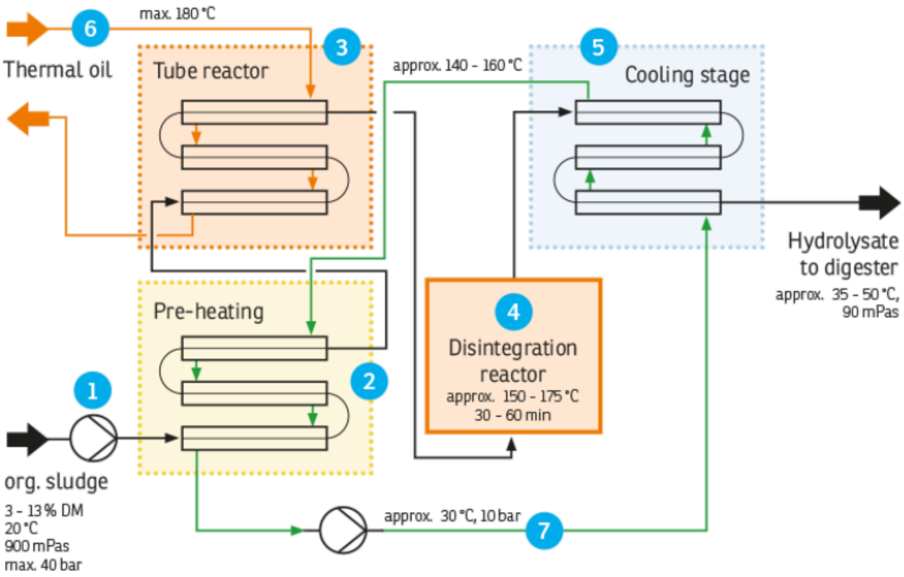

Figure 10: LysoTherm® process [Eliquo Stulz GmbH]

Table 14 gives an overview of results obtained at large scale plants applying the thermal hydrolysis processes described above. Only Exelys obtained VS-degradation rates and biogas yields for mixed sludge which exceeds the single stage mesophilic maximum significantly due to the DLD configuration. Yet TurboTec and LysoTherm outperformed single stage mesophilic digestion, taking into account that only excess sludge was treated in the TH unit. Thermal hydrolysis has a negative impact on the plant due to increased polymer demand and return load, with (DWA 2015) reporting an average increase of 470 mg-NH_4-N/l and of 6 kg-polymer/t-DS, respectively.

Table 14: Thermal Hydrolysis > 100 °C (CAMBI and Exelys + DLD: mixed sludge, TurboTec and Lysotherm: excess sludge, DWA: no info)

Performance Indicators						References
Degradation rate [%-VS$_{degraded}$]	Biogas yield [Nm^3/t-VS$_{fed}$]	Dewaterability [%-DS]	Return load (NH_4-N) [-]	Energy consumption [kWh/m$^3_{sludge}$]	Capital Expenditure [€/PE]	
68	440	25-30 (winkle press, polymer demand + 48 %)	Medium-high (1096-1420 mg/l)	7.2 kWh$_{el}$/m^3 116 kWh$_{heat}$/m^3	20.38 €/PE	(Bormann et al. 2009, Kopmann and Kopp 2010, Kopmann 2012, Nilsen) (CAMBI)
48	410 per VS$_{fed}$ (no primary clarifier)	29-30	+ 30-40% of NH_4-N in return flow	52 kWh$_{el}$/t TS 620 kWh$_{heat}$/t TS		(Boehler et al. , Hol et al. 2014) (TurboTec)
>65	600	30-32 (centrifuge)				(Kjaer et al. 2016) (Exelys + DLD)
50-54	431 Nm^3/t-VS$_{fed}$ (refers to treated ES)	28 (centrifuge)	155 kg NH_4-N/d	5.4 kWh$_{el}$/m^3 39 kWh$_{heat}$/m^3	9.64 €/PE	(Hüer 2015, Knörle et al. 2016) (LysoTherm)
53.8	550	33.2	High (1788 mg/l)			mean value Lysotherm and CAMBI (DWA 2015)

3.6.3. Chemical disintegration

Alkali and acid hydrolysis

The addition of alkali or acid to the sludge increases hydrolysis rate which is proportional to the concentration of H^+ and OH^- ions. It causes the cleavage of carbohydrates, proteins and other biopolymers and thus dissolution of the cell wall. Sludge solubilization is enhanced and subsequently biogas production and VS-degradation improve. Higher treatment temperatures which are normally driven by chemical processes generate secondary effects similar to those of thermal hydrolysis and accelerate chemical cleavage which allows shorter contact times. Alkali treatment is more common than acid treatment because alkaline hydrolysis of the cell wall lipids releases more organic substances. No full scale applications for acid hydrolysis of municipal sewage sludge are known today (Carrere et al. 2010, DWA 2015), even though a full-scale plant was in operation using the KREPRO® process (Karlsson 2001).

The order of efficiency of alkali reagents is NaOH > KOH > $Mg(OH)_2$ > $Ca(OH)_2$ (Carrere et al. 2010). Consequently, NaOH is mainly used in full scale applications such as the patented PONDUS® process (Figure 11).

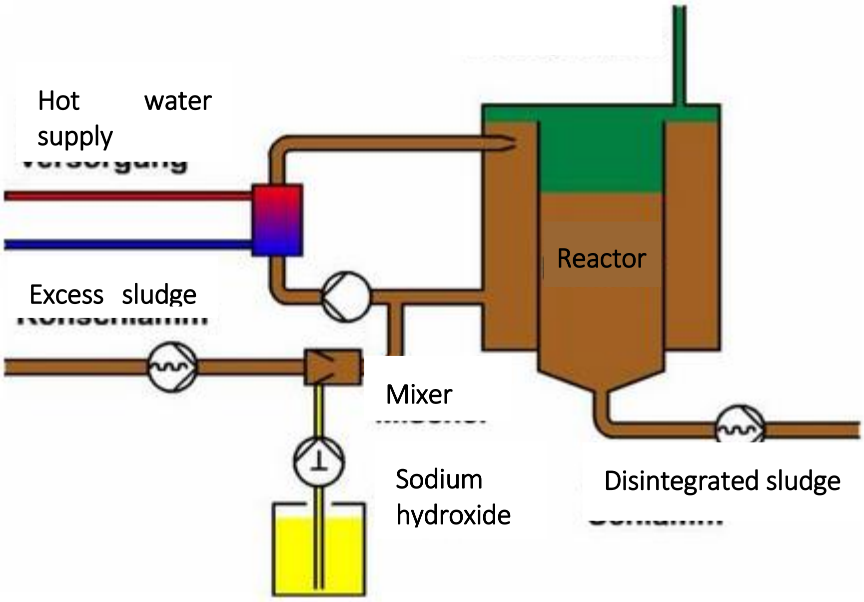

Figure 11: PONDUS® process (PONDUS GmbH)

During the process 2 L of NaOH are added per m³ of pre-thickened excess sludge (4-8%-DS), which is then mixed into a recirculation stream of hot hydrolyzed sludge coming back from the reactor. Overlal duration of hydrolyzation is about 2 h, and reaction temperature is kept constant at 65-70 °C. The disintegrated sludge is neutralized by the release of organic acids resulting from cell disruption. Table 15 summarizes the results obtained from a full scale plant in Uelzen (northern Germany) and from laboratory tests adopted from the guidelines of the German water association. The above single stage mesophilic maximum biogas yield from the guidelines is not confirmed by the full scale application, even though an increase in biogas yield of 100 $Nm^3/kg\text{-}VS_{fed}$ was achieved by implementation of the PONDUS unit. The higher degradation rate of PONDUS compared to the guideline figures can be explained by having an initial VS-degradation rate of 66 % at the Uelzen WWTP, due to a great share of easily bioavailable co-substrate and a high HRT of 42 d. The decrease in polymer demand is not confirmed by the guideline values and might differ because of different dewatering techniques and the special conditions at Uelzen WWTP.

Table 15: Alkali hydrolysis (Pondus: mixed sludge, DWA: no info)

Performance Indicators						References
Degradation rate [%-$VS_{degraded}$]	Biogas yield [$Nm^3/t\text{-}VS_{fed}$]	Dewaterability [%-DS]	Return load (NH_4-N) [-]	Energy consumption [kWh/m^3_{sludge}]	Capital Expenditure [€/PE]	
70.4	430	22 (- 3 kg polymer/ t DS)				(Kahrs and Hermanussen 2015) (Pondus)
58	546	31.3 (+ 2.1 kg polymer/t DS)	High (1439 mg/l)	1,5 kWh_{el}/m^3 50 kWh_{heat}/m^3 (without recovery) (Ndoh Rossier et al. 2007)		(DWA 2015)

Oxidation

Chemical treatment with oxidation agents such as ozone or hydrogen peroxide mainly aims on the destruction of unsaturated fatty acids in the cell membrane of microorganisms. Afterwards the oxidation agent can enter the cell and react with the cytoplasm, and at the same time cytoplasm can be released through the damaged cell wall. (Winter 2003)

When the oxidation agent is injected, two parallel reactions can be observed causing the above mentioned effect. First the direct oxidation which is comparatively slow and selective, and second the fast and unselective reaction of hydroxyl radicals produced by radical forming substances or by excitation (for example by UV radiation). (Winter 2003)

Ozone is the most widely spread oxidation agent for sewage sludge and was first applied in wastewater treatment for the reduction of waste activated sludge. With increasing ozone dose, the degree of disintegration normally rises (Winter 2003). If ozone is overdosed, the solubilization is reduced due to oxidation of the solubilized compounds, and the production of inert soluble organic fractions is increased (Carrere et al. 2010). Optimum ozone dose was found to be 0.01 to 0.15 kg O3/kg DS for oxidation of waste activated sludge and 0.02 to 0.87 kg O3/kg DS for digested sludge (Winter 2003).

Table 16 shows the results of a plant were ozonation of excess sludge prior to anaerobic digestion was tested for 13 weeks. The ozonation was operated continuously with an average ozone dose of 0.052 kg O_3/kg DS. Biogas yield and VS-degradation rate exceeded mesophilic single stage maximum. In comparison to other disintegration methods, the load of return flow from oxidation is remarkably higher, especially in terms of COD. That indicates that part of the solubilized COD is not depleted in the digester due to the ozone not only destroying cells but also reacting with the cell components. It is likely that this COD fraction will not be reduced much in the aerobic biological step of the WWTP and thus affect WWTP effluent quality.

Table 16: Oxidation with ozone (mixed sludge)

Performance Indicators						References
Degradation rate $[\%\text{-}VS_{degraded}]$	Biogas yield $[Nm^3/t\text{-}VS_{fed}]$	Dewaterability [%-DS]	Return load (NH_4-N) [-]	Energy consumption $[kWh/m^3_{sludge}]$	Capital Expenditure [€/PE]	
58.4	550	+2.4% DS (increase in polymer demand +29%)	Low (410 mg/l or +16 %, and +60 % COD)	23.8 kWh_{el}/m^3 (ozone generation and pumping)	18 €/PE	(Winter 2003, Schmelz and Müller 2004)

Hydrogen peroxide is another oxidation agent that can be applied to activated or digested sludge. Combined with divalent iron it causes a Fenton reaction and produces hydroxyl radicals. It turned out to be more efficient for post-treatment at high temperatures on the recirculation loop than for pre-treatment. (Carrere et al. 2010)

3.6.4. Biological lysis

Enzymes

During the hydrolysis step of AD, exoenzymes are produced to break down undissolved macro biopolymers to smaller dissolved fragments which can be absorbed by acidogenic microorganisms. The objective of enzymatic treatment of sludge is to support this hydrolysis activity (which is the rate limiting step) by dedicated dosing of a solution of exoenzymes.

Enzymes act as a catalyst and are not consumed in the process. They are biologically degradable and therefore not harmful to the environment.

Usually a mixture of different hydrolytic enzymes such as cellulase, amylase, protease and lipase is added either directly into the digester or via a pump into the feed line. Since higher temperature accelerates enzymatic reactions, (Recktenwald et al. 2008) added the enzyme solution to the heat exchange loop to give the enzymes extra activation time and mixing. The optimum dosage was found to be 500-800 mg Enzymes/kg-oTR (Burbaum et al. 2002).

The performance of large scale reactors (Table 17) shows VS-degradation rates and biogas yield above single stage mesophilic maximum. Since enzymatic treatment only enhances the intrinsic bioavailability, processes which already obtain good digestion results (i.e. performance at the upper range of single stage digesters mesophilic) are not likely to be improved greatly by the addition of enzymes.

Since enzymatic treatment does not require costly extra equipment for the application or for treatment of the return flow it might be a low-cost option for plants with poor digester performance.

Table 17: Enzymatic treatment (mixed sludge)

Performance Indicators						References
Degradation rate [%-$VS_{degraded}$]	Biogas yield [Nm^3/t-VS_{fed}]	Dewater-ability [%-DS]	Return load (NH_4-N) [-]	Energy consumption [kWh/m^3_{sludge}]	Capital Expenditure [€/PE]	
47-52	370-562	31 (centrifuge)	Low			(Burbaum et al. 2002, Recktenwald et al. 2008)

3.7. Other processes

Besides the advanced AD processes that have been realized in full-scale, other promising processes are described below which have not reached full maturity yet. Full scale applications of these processes have not been realized until now, but laboratory and pilot studies have shown that they have potential to contribute to the objective of improved sludge digestion and energy-positive WWTPs. Since further research has to be conducted to obtain large scale results, they are not included in Table 19.

3.7.1. Microaeration

The previous methods all aimed at the enhancement of the AD process. Microaeration (i.e. dosing small amounts of oxygen or air into the AD) on the contrary aims at improving biogas quality by removing hydrogen sulfate. Since H_2S causes corrosion of concrete and steel, negatively affects the function of the CHP unit, limits utilization potential of biogas and is toxic to humans, it is usually removed with great effort from the biogas (Krayzelova et al. 2015). Microaerobic treatment offers a biologically, in-situ alternative to oxidize sulfide to elemental sulfur before it becomes part of the biogas.

Usually biogas from municipal sewage sludge digestion does not contain high hydrogen sulfide concentrations (< 50 mg/m^3 (DWA 2010)) as iron is usually added during the WWT process and fixes the sulfide as FeS. But for biogas from different co-substrates or in WWTPs with high industrial share in the influent, H2S concentration can rise up to 10,000 mg/m^3 (DWA 2010) and may require extra addition of FeCl3. To reduce FeCl3 demand microaeration can be applied to the digester.

Theoretically microaeration of an AD seems to be counterproductive to the digester performance as it introduces aerobic conditions, but studies have shown that the anaerobic community will not be inhibited and the overall digester performance is only slightly affected (Fdz-Polanco et al. 2009, Jenicek et al. 2014). In microaeration, oxygen is dosed carefully into the AD process, and it is completely and very quickly depleted by chemical reactions and facultative anaerobic microorganisms.

Microaerobic treatment can be applied in three different ways to the AD. Either the recirculating biogas or sludge is treated with oxygen (Fdz-Polanco et al. 2009) or the digester is aerated directly (Jenicek et al. 2014). If the reactor is aerated directly, it has to be decided whether oxygen is dosed into the headspace or into the liquid phase.

Dosing oxygen into the liquid phase can cause non-specific oxidation, which consumes part of the oxygen but at the same time it decreases sulfide toxicity towards methanogens. Aerating the headspace instead, oxygen can react directly with the hydrogen sulfide and no oxygen will be lost. What is more, studies with different headspace volumes showed the H2S removal mainly takes place in the head space, since reactors with no headspaces did not respond to aeration whereas reactors with large headspace volumes obtained complete hydrogen sulfide removal. (Krayzelova et al. 2015)

The gaseous aeration medium can be either pure oxygen or air. To ensure that the oxygen is completely consumed by oxidation of sulfide and no residues remain which could inhibit the anaerobic process, the initial H2S concentration in the biogas should be taken into account to determine the O2 volume to be injected into the digester. (Krayzelova et al. 2015) suggest an oxygen dosage (or equivalent air) between 0.3 and 3 % of produced biogas.

If air was used for aeration instead of pure oxygen, an increase of nitrogen in the biogas was detected which lowered the methane content. Another issue caused by microaeration is the clogging of walls and pipes with elemental sulfur, leading to shorter cleaning intervals of the digester (Jenicek et al. 2014). During microaerobic treatment it is crucial to keep the residual oxygen concentration in the anaerobic reactor very low not only to prevent inhibition of anaerobic activity but also to minimize the risk of fire and explosion which can occur when oxygen concentration in the biogas exceeds the limiting oxygen concentration (Diaz et al. 2015).

Until now microaeration has only been tested in single stage mesophilic pilot scale reactors. Based upon these results (Diaz et al. 2015) created scenarios for different microaerobic applications in full scale reactors (150,000 PE). The use of concentrated oxygen (air with an oxygen concentration higher than 95 % v) produced from air by a pressure swing adsorption (PSA) generator turned out to be economically most efficient.

By comparing the results of the scenario to the benchmark figures in Table 3, it becomes clear that microaerobic treatment has no negative impact on the overall digester performance (e.g. obtaining 480 Nm^3-biogas/t-VSfed and a degradation rate of 47 %) (Diaz et al. 2015). H2S removal efficiency was 99% and higher (Jenicek et al. 2014). Although the microaerobic treatment requires additional energy, 80 % of the operating costs might be saved in total, in comparison to state-of-the-art treatment where FeCl3 is added to the digester (Diaz et al. 2015). Therefore a combination of microaeration and a process to increase biodegradability could reduce costs and improve both, biogas quantity and quality.

3.7.2. **Aerobic post-stabilization of AD sludge**

Stabilization through further degradation of VS from digested sludge can be achieved by aerobic post treatment. Even though additional aerobic VS reduction is ecologically not useful for incineration and increases energy costs for aeration, it can be economically relevant in case of decentralized incineration plants (Parravicini et al. 2006).

(Parravicini et al. 2006) found aerobic post treatment of digested sludge to be more efficient in terms of VS degradation than anaerobic post treatment. They suggest that under aerobic conditions hydrolysis of the remaining organic matter is improved.

(Tomei et al. 2015) confirm that it is possible to achieve 61% VS reduction of waste activated sludge by aerobic post-stabilization (47% by anaerobic single stage mesophilic digestion and 26 % by aerobic post-stabilization). Moreover nitrogen removal of up to 62 % can be achieved by simultaneous nitrification-denitrification which would decrease nitrogen load in the return flow and without requiring extra treatment of the dewatering effluent.

3.7.3. **Dark fermentation**

Dark fermentation aims on the production of hydrogen by anaerobic bacteria. Looking at the upper pathway of the four stages of anaerobic digestion presented in Figure 1, it becomes clear that during acidogenesis, under the right conditions (especially a low hydrogen partial pressure $pH_2 < 10^{-4}$) hydrogen, carbon dioxide and short chain carboxylic acids are produced from carbohydrates. To stimulate dark fermentation pH_2, pH and HRT have to be adjusted accordingly (Levin 2004). Furthermore higher treatment temperatures, i.e. thermophilic instead of mesophilic conditions and a carbonhydrate rich substrate promote H_2 production (Chong et al. 2009).

Carbohydrate concentration in municipal sewage sludge and especially in excess sludge is relatively low (Mergelmeyer and Kolisch 2014) which is why dark fermentation is only efficient for co-digestion of sewage sludge and municipal organic solid waste or food waste (De Gioannis et al. 2013, Gottardo et al. 2015).

In practice, the end products of the heterogenic substrates will not only be the above mentioned, but will also include alcohols which have to be degraded further by acetogenesis. Hence, a system of two reactors in a row can be used, in which dark fermentation takes place in the first and methanogenises takes place in the second reactor. A high organic loading rate, a short HRT (≈3 d) and a low pH (5-6.5) in the first digester enhance enzymatic activity and inhibit methanogenic activity. (Gottardo et al. 2013)

Pilot tests form (Gottardo et al. 2015) who used a mixture of sewage sludge and organic fraction of municipal solid waste (OFMSW) as substrate (50:50 on VS basis), showed that under thermophilic conditions in the whole system, the gas obtained from the first digester (3.3 d HRT and 18 kg $VS/m^3 \cdot d$) contained 40 %v hydrogen and the gas from the second digester (15 d HRT and 3.5 kg $VS/m^3 \cdot d$) 67 %v methane. The mixture of the two gases consisted of 7.5 %v H_2, 33.9 %v CO_2 and 58.6 %v CH_4. The higher share in H_2 improves combustion efficiency (Porpatham et al. 2007, Gottardo et al. 2015) (average biogas contains 0.02 %v H_2 (DVGW 2014)). It was not reported whether the higher H_2 share could compensate the lower methane share in terms of electricity production. Despite increasing combustion efficiency hydrogen can also be used as fuel if collected separately.

The dark fermentation process flow is similar to the two stage high load digestion. The main difference is the organic loading rate which is higher in dark fermentation due to the OFMSW. The composition of the biogas obtained from high load digestion is not reported. Still it can be assumed that the H_2 share in the high load digestion gas originating from sewage sludge is negligible because H_2 mainly results from the digestion of carbohydrates which were found to be relatively low in sewage sludge, but higher in OFMSW (Ge et al. 2011, Mergelmeyer and Kolisch 2014).

Table 18: Dark Fermentation (OFMSW and mixed sludge, 50:50 on VS basis)

Performance Indicators						References
Degradation rate	Biogas yield	Dewaterability	Return load (NH_4-N)	Energy consumption	Capital Expenditure	
[%-$VS_{degraded}$]	*[Nm^3/t-VS_{fed}]*	*[%-DS]*	*[-]*	*[kWh/m^3_{sludge}]*	*[€/PE]*	
75	546		High (1,328 mg/l in reactor effluent)			(Gottardo et al. 2015)

4. Performance overview

Table 19 provides an overview of all processes for advanced AD which are based on full-scale references. For each type of processes, data of one reference was selected to be representative for the technology. In some cases, other data was complemented if key performance indicators were not completely reported in the literature.

It has to be noted that the references are based on different types of sludge: while most are working on mixed sludge and can be directly benchmarked to single-stage mesophilic digestion of mixed sludge, some processes work on excess sludge only. These processes should be benchmarked against the predicted VS degradation and biogas yield for excess sludge only (cf. Figure 12).

Table 19: Performance Overview

Process	Substrate	Processing time		Performance indicators						PE	Notes	References
		HRT (first stage) [d]	HRT (main stage) [d]	Degradation rate [% $VS_{degraded}$]	Biogas yield [$Nm^3/t\ VS_{fed}$]	Dewaterability [% DS]	Return load (NH_4-N) [-]	Energy consumption [kWh/m^3_{sludge}]	Capital expenditure [€/PE]			
Single stage mesophilic	Mixed Sludge		>30	45-50	400-500	20-30 (belt filter press) 20-32 (centrifuge) 28-40 (chamber filter press)	Low	0.04 kWh_{el} and 0.5 kWh_{heat} per kg-VSfed	107 €/PE (10.000-25.000 PE, new construction of AD unit + CHP+ primary clarifier) (BLU 2015)			(DWA 2003) (Rosenwinkel 2015) (Carrere et al. 2010)
Thermophilic	Mixed Sludge		13	52.7	500	25 (by centrifuge)	High (1,400 mg/l)	0.03 kWh_{el} and 1 kWh_{heat} per kg-VSfed (Carrere et al. 2010)			Change from TPAD to single-stage thermophilic	(Dichtl and Klinksieg 2004)
Two-stage cascading mesophilic	Mixed Sludge	8	10	49	450	27 (centrifuge)	High (1254 mg/l)	4 kWh_{el} and 20 kWh_{heat}	Reconstruction of single-stage digestors into cascade	1,400,000		(Remy 2012)
Two-stage mesophilic	Mixed Sludge	3	11-15	60-65	540-585							(EPA 2006)

Process	Substrate	Processing time		Performance indicators						PE	Notes	References
		HRT (first stage)	HRT (main stage)	Degradation rate	Biogas yield	Dewaterability	Return load (NH_4-N)	Energy consumption	Capital expenditure			
		[d]	*[d]*	*[% $VS_{degraded}$]*	*[$Nm^3/t\ VS_{fed}$]*	*[% DS]*	*[-]*	*[kWh/m^3_{sludge}]*	*[€/PE]*			
High load digestion (two stages)	Mixed sludge	5	20	60	559	27-28, decrease in polymer demand				360,000	High HRT in the second stage because existing system was extended.	(Kempter-Regel et al. 2003)
High load digestion (single stage, microfiltration)	Mixed Sludge	HRT 7 SRT 8.6		40	411	30 (belt filter press)	Medium (1200 mg/l)	4,83 kWh_{el} (microfiltration + AD)	103 (new construction of AD unit + CHP+ primary clarifier, two stage high load)	26,700	WWTP is overloaded by a factor 4.	(Kempter-Regel et al. 2003)
TPAD (thermophilic-mesophilic)	Excess Sludge	9	18	45	454	27 (by centrifuge)	Medium (800 mg/l) (Dichtl and Klinksieg 2004)					(Krugel et al. 2006)
TPAD (mesophilic-thermophilic)	Mixed Sludge	10	10.6	54	591	32		3.57 kWh_{el} 28.6 kWh_{heat}	75 €/PE (new construction of AD unit + CHP)	60,000		(Merz et al. 1999)

Process	Sub-strate	Processing time		Performance indicators						PE	Notes	References
		HRT (first stage)	HRT (main stage)	Degradation rate	Biogas yield	Dewaterability	Return load (NH_4-N)	Energy consumption	Capital expenditure			
		[d]	*[d]*	*[% $VS_{degraded}$]*	*[Nm^3/t VS_{fed}]*	*[% DS]*	*[-]*	*[kWh/m^3_{sludge}]*	*[€/PE]*			
Mechanical disintegration, high pressure homogenization	Mixed sludge		16-23	57	478	41.9 (chamber filter press, constant polymer demand = 6 kg/t-DS)	Low (671 mg TN/l)	5.5 kWh_{el}/m^3 sludge treated (DWA 2015)	2 €/PE (pressure homogenizer + installation for 100,000 PE))	55,000	With upstream thickening.	(Sievers et al. 2006)
Mechanical disintegration, ultrasonic	Mixed sludge		22.5 (Carrere et al. 2010)	60.4	442	Increased polymer demand, -0.5% DS (Schmelz and Müller 2004)	Low (446 mg/l or +5%) (Schmelz and Müller 2004)	2.4 kWh_{el}/m^3 ES for operating US unit	0,97	330,000		(Neis et al. 2008)
Mechanical disintegration, lysate centrifuge	Mixed sludge		19	> 60 (Carrere et al. 2010)	362	31.5 ((Jenicek et al. 2013))	Low (491 mg/l) (Winter 2003)	11.4 kWh_{el} per m^3 ES (Winter 2003)	1,22 €/PE, reconstruction of existing lysate centrifuge (Winter 2003)	650,500	Improvements by sludge thickening, less by floc/cell disruption	(Carrere et al. 2010)
Mechanical disintegration, stirred ball mill	Mixed sludge		17-18	49.5	550	Increased polymer demand (+7.4%) - 2.9 % DS compared to reference test	Low (417 mg/l)	21.1 kWh_{el} per m^3 ES	19.76 €/PE, stirred bead mill including housing and machinery	17,000	Stirred bead mill was tested for 13 weeks	(Winter 2003)

Process	Sub-strate	Processing time		Performance indicators						PE	Notes	References
		HRT (first stage) *[d]*	HRT (main stage) *[d]*	Degradation rate *[% VS$_{degraded}$]*	Biogas yield *[Nm^3/t VS$_{fed}$]*	Dewaterability *[% DS]*	Return load (NH$_4$-N) *[-]*	Energy consumption *[kWh/m^3$_{sludge}$]*	Capital expenditure *[€/PE]*			
Thermal Hydrolysis (CAMBI)	Mixed sludge		15-22	68	440	25-30 (winkle press, polymer demand +48%)	Medium-high (1096-1420 mg/l)	7.2 kWh$_{el}$ 116 kWh$_{heat}$	20.38	100,000 - 250,000		(Nilsen 2015)
Thermal Hydrolysis (TurboTec)	Excess sludge		20	48	410	29	+ 30-40% in return flow	52 kWh$_{el}$/t TS 620 kWh$_{heat}$/t TS		330,000		(Boehler et al. , Hol et al. 2014)
Thermal Hydrolysis (Exelys)	Mixed sludge		17	>65	600	30-32 (centrifuge)				630,000	Two-stage DLD system (digestion-thermal hydrolysis-digestion)	(Kjaer et al. 2016)
Thermal Hydrolysis (Lyso-Therm)	Mixed sludge		20	50-54	431 (refers to treated ES)	28 (centrifuge)	155 kg NH$_4$-N/d	5.4 kWh$_{el}$ and 39.2 kWh$_{heat}$	9.64 €/PE	140,000		(Hüer 2015, Knörle et al. 2016)
Chemical disintegration,alkaline treatment (Pondus)	Mixed sludge (industria + municipal)		42	70.4	430	22 (- 3 kg polymer/ t DS)	High (1439 mg/l) (DWA 2015)	1,5 kWh$_{el}$ 50 kWh$_{heat}$ (without recovery) (Ndoh Rossier et al. 2007)			Decrease in polymer demand was not confirmed in lab studies	(Kahrs and Hermanussen 2015)

Process	**Sub-strate**	**Processing time**		**Performance indicators**						**PE**	**Notes**	**References**
		HRT (first stage) *[d]*	HRT (main stage) *[d]*	Degradation rate *[% $VS_{degraded}$]*	Biogas yield *[$Nm^3/t\ VS_{fed}$]*	Dewaterability *[% DS]*	Return load (NH_4-N) *[-]*	Energy consumption *[kWh/m^3_{sludge}]*	Capital expenditure *[€/PE]*			
Chemical disintegration, ozone	Mixed sludge		17-18	58.4	550	+2.4% DS (increase in polymer demand 28.6%)	Low (411 mg/ or +16 %) (+60 % COD)	23.8 kWh_{el} (ozone generation and pumping)	17.72 €/PE	17,000	Ozonation was tested for 13 weeks	(Winter 2003)
Biological lysis, Enzymes	Mixed Sludge		> 20	47-52	370-562	31 (centrifuge)	Low			100,000 – 430,000		(Recktenwald et al. 2008)

In Figure 12 and Figure 13, biogas yields of the studied processes in Table 19 are related to HRT (total HRT = all stages combined) and compared to the expected biogas yields from primary, excess and mixed sludge of single stage mesophilic digestion as a function of HRT. Most of the plants use mixed sludge in AD, whereas some processes give data only for excess sludge digestion (highlighted in red). Figure 12 shows the results of full-scale plants using methods of sludge disintegration (biological, chemical, physical), whereas Figure 13 shows full-scale plants using process modifications of AD (e.g. thermophilic, two-stage, high load). The grey area in both graphs shows the average biogas production of state-of-the-art single stage mesophilic digestion as a mean of three references (Kapp 1984, Geshnigani 2013, Mergelmeyer and Kolisch 2014).

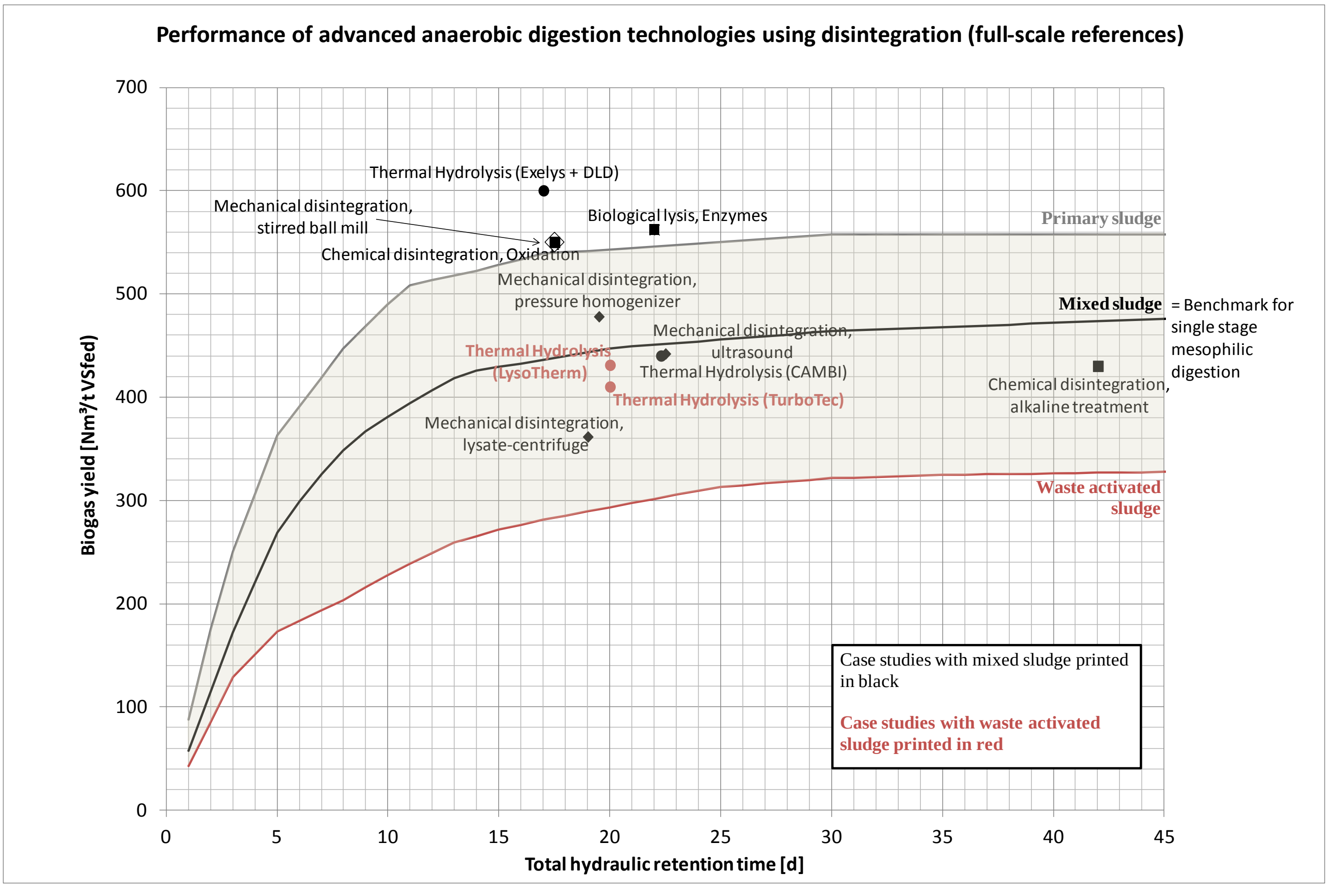

Figure 12: Biogas yield and total hydraulic retention time of advanced anaerobic digestion technologies using disintegration (data from full-scale references)

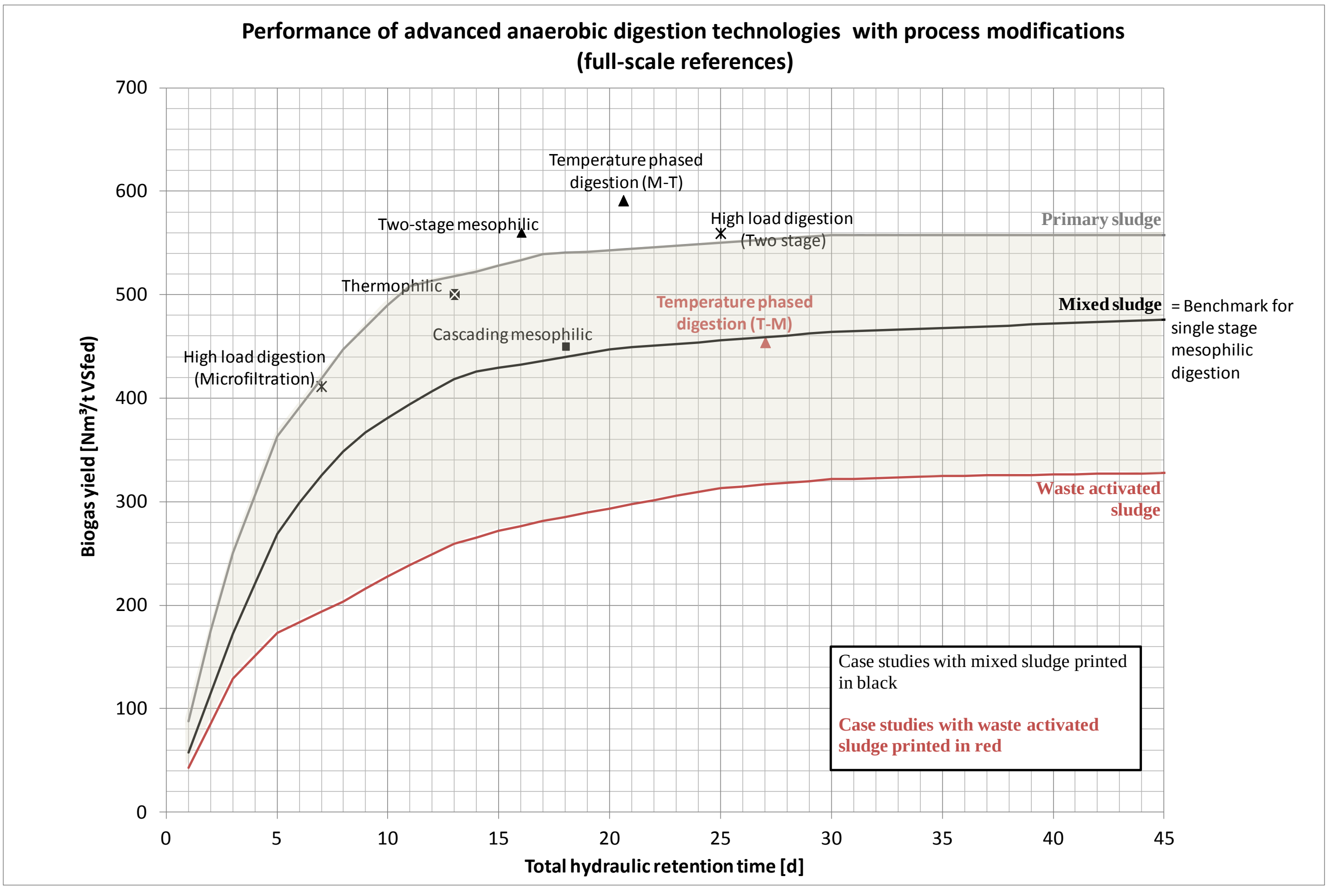

Figure 13: Biogas yield and total hydraulic retention time of advanced anaerobic digestion technologies using process modifications of AD (data from full-scale references)

5. Conclusion

The evaluation of the full-scale case studies showed that advanced processes for AD have the potential to contribute to the goal of energy positive WWTPs by increasing biogas yield from sludge. However, major difficulties arise while comparing full-scale data of different WWTPs, as site-specific characteristics of process design and sludge properties have a large impact on absolute results of the advanced AD processes. Naturally, a more comprehensive and consistent data collection would help to increase the reliability and comparability of the results.

Nevertheless the following conclusions can be drawn from the studied data:

- Single-stage mesophilic digestion with 20d HRT as a standard process for anaerobic digestion yields around 420 NL biogas per kg VS_{in} for mixed sludge and 300 NL biogas per kg VS_{in} for waste activated sludge sludge under optimium conditions. Related VS reduction rates are around 50% for mixed and 37% for excess sludge.
- Advanced processes for sludge digestion can generally increase VS reduction and biogas yield. An increase in VS reduction usually leads to a higher return load in NH_4-N.

The project “Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration” (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

- Processes working on excess sludge (namely TPAD (thermophilic-mesophilic) and thermal hydrolysis (TurboTec and Lysotherm)) increase biogas production from excess sludge by 15-40% compared to single stage mesophilic digesters.
- A VS-degradation rate above 60 % is most likely to be achieved by applying any form of thermal hydrolysis. Furthermore VS-degradation rate seems not necessarily correlated with biogas production.
- TPAD and high load digestion perform well in terms of biogas production and VS-degradation, the latter also at lower HRT. Still more data (e.g. energy consumption) has to be obtained to decide whether they should be preferred over thermal hydrolysis.
- Two-stage processes can improve VS degradation (60-65%) and biogas yield (> 540 NL/kg VS_{in}) of mixed sludge. Whereas cascading reactors improve mixing and control of HRT, real two-stage systems with separate reaction steps can lower HRT and increase OLR by providing optimum conditions for the different stages of AD.
- Usually HRT of less than 20 days can be realized by advanced anaerobic treatment processes. Since the advanced processes are often implemented in existing AD units which were originally designed for single stage mesophilic processes, digesters have large volumes causing longer HRTs which do not necessarily correspond to the minimum HRT required for VS reduction in advanced mode.
- An enhanced hydrolysis and degradation process causes an increase in NH_4-N load of the dewatering effluent. The impact from disintegration methods (except biological disintegration) is stronger than from high load digestion or TPAD.
- By relating specific costs for the installation of advanced AD processes to the PE, it becomes clear that scaling effects appear at bigger plants. Higher costs of advanced AD processes are likely at smaller WWTPs, but will most probably be off-set by rising sludge disposal costs in the future, making them economically attractice also for smaller WWTPs.
- Mechanical disintegration methods have two major disadvantages: a) electrical energy demand is relatively high and difficult to compensate by higher biogas production and b) improved dewaterability of the sludge is often accompanied by increased specific polymer demand. In addition, sludge often has to be thickened before mechanical disintegration and the effects of thickening and mechanical disintegration cannot be properly distinguished.
- Other advanced processes such as microaeration and aerobic post-stabilisation are helpful to overcome specific problems of biogas management (e.g. removal of H_2S from biogas) or increase VS degradation aerobically to reduce sludge disposal costs.
- Dark fermentation could be a promosing process for sewage sludge digestion, producing hydrogen as an energy carrier. However, existing studies focus on other substrates and are still in lab-scale, so that further research in this field is required.

6. References

Abelleira-Pereira, J. M., S. I. Perez-Elvira, J. Sanchez-Oneto, R. de la Cruz, J. R. Portela and E. Nebot (2015). "Enhancement of methane production in mesophilic anaerobic digestion of secondary sewage sludge by advanced thermal hydrolysis pretreatment." Water Research **71**: 330-340.

Berg, S., M. Berg, M. Lüdtke and C. Baresel (2016). Extended Sludge Retention Time in a full Scale anaerobic Digester at Himmerfjärden WWTP. 2nd IWA Conference on Holistic Sludge Management. Malmö, Sweden, International Water Association.

BLU (2015). Nachrüstung einer Klärschlammfaulung auf kleinen Kläranlagen, Bayrisches Landesamt für Umwelt.

Boehler, M., H. Siegrist, J. Luning, A. Heisele, L. Van Dijk and M. Schachtler "Thermal hydrolysis of sludge to improve biogas yield and reduce sludge disposal costs." Manuscript Draft Water Science and Technology.

Bonkoski, N. (2013). Continuous Thermal Hydrolysis. The Path to Energy Neutrality, Water Environment Association of Texas.

Bormann, H., M. Sievers and W. Ewert (2009). Auswirkung der thermischen klärschlammhydrolyse und der prozessintegrierten Nährstoffrückgewinnung auf die Stoffstrom- und Energiebilanzen auf Klärnanlagen, Deutsche Bundesstiftung Umwelt.

Braguglia, C. M., N. Carozza, M. C. Gagliano, A. Gallipoli, A. Gianico, S. Rossetti, J. Suschka, M. C. Tomei and G. Mininni (2014). "Advanced anaerobic processes to enhance waste activated sludge stabilization." Water Sci Technol **69**(8): 1728-1734.

Burbaum, H., T. Dickmann, K. Kéry, I. Pascik and H. Radermacher (2002). "Biokatalytische Verbesserung der Klärschlammfaulung durch Enzyme." KA - Abwasser, Abfall(8).

Carrere, H., C. Dumas, A. Battimelli, D. J. Batstone, J. P. Delgenes, J. P. Steyer and I. Ferrer (2010). "Pretreatment methods to improve sludge anaerobic degradability: a review." Journal of Hazardous Materials **183**(1-3): 1-15.

Chong, M.-L., V. Sabaratnam, Y. Shirai and M. A. Hassan (2009). "Biohydrogen production from biomass and industrial wastes by dark fermentation." International Journal of Hydrogen Energy **34**(8): 3277-3287.

De Gioannis, G., A. Muntoni, A. Polettini and R. Pomi (2013). "A review of dark fermentative hydrogen production from biodegradable municipal waste fractions." Waste Manag **33**(6): 1345-1361.

Deublein, D. and A. Steinhauser (2010). Biogas from Waste and Renewable Resources, Wiley-VCH Verlag GmbH & Co. KGaA.

Diaz, I., I. Ramos and M. Fdz-Polanco (2015). "Economic analysis of microaerobic removal of H2S from biogas in full-scale sludge digesters." Bioresour Technol **192**: 280-286.

Dichtl, N. and K. Klinksieg (2004). Abschlussbericht zur wissenschaftlichen Begleitung der Umstellung der Schlammfaulung auf thermophilen Betrieb des Klärwerks Braunschweig-Steinhof, Technische Universität Braunschweig - Institut für Siedlungswasserwirtschaft.

DVGW (2014). Einsatz von industriellen und kommunalen Abfallstofen für die Biogaseinspeisung. Bonn, Deutscher Verein des Gas- und Wasserfache e.V.

DWA (2003). Biologische Stabilisierung von Klärschlamm. ATV-DVWK-M 368. A. u. A. e. V. Deutsche Vereinigung für Wasserwirtschaft.

DWA (2010). Herkunft, Aufbereitung und Verwertung von Biogasen. Merkblatt DWA-M 363. A. u. A. e. V. Deutsche Vereinigung für Wasserwirtschaft.

DWA (2013). 25th Benchmarking of German wastewater treatment plants, DWA.

DWA (2015). Merkblatt DWA-M 302 Klärschlammdesintegration Desintegration Gelbdruck. DWA-M 302. DWA.

EPA (2006). Biosolids Technology Fact Sheet: Multi-stage Anaerobic Digestion, US-EPA 832-F-06-031, Office of Water.

Fdz-Polanco, M., I. Diaz, S. I. Perez, A. C. Lopes and F. Fdz-Polanco (2009). "Hydrogen sulphide removal in the anaerobic digestion of sludge by micro-aerobic processes: pilot plant experience." Water Sci Technol **60**(12): 3045-3050.

Gary, D., R. Morton, C.-C. Tang and R. Horvath (2007). "The Effect of the Microsludge; Treatment Process on Anaerobic Digestion Performance." Proceedings of the Water Environment Federation **2007**(17): 1724-1738.

Ge, H., P. D. Jensen and D. J. Batstone (2010). "Pre-treatment mechanisms during thermophilic-mesophilic temperature phased anaerobic digestion of primary sludge." Water Research **44**: 123-130.

Ge, H., P. D. Jensen and D. J. Batstone (2011). "Temperature phased anaerobic digestion increases apparent hydrolysis rate for waste activated sludge." Water Research **45**(4): 1597-1606.

Geshnigani, M. A. (2013). Methane production from seperate digestion of primary and biological sludge. Master of science, Lund Univerisity.

Gottardo, M., C. Cavinato, D. Bolzonella and P. Pavan (2013). "Dark Fermentation Optimization by anaerobic digested sludge: recirculation effects of hydrogen production." Chemical Engineering Transactions **32**: 997-1002.

Gottardo, M., F. Micolucci, A. Mattioli, S. Faggian, C. Cavinato and P. Pavan (2015). "Hydrogen and Methane Production from Biowaste and Sewage Sludge by two Phase Anaerobic Codigestion." Chemical Engineering Transactions **43**: 379-384.

Haberkern, B., W. Maier and U. Schneider (2008). Steigerung der Energieeffizienz auf kommunalen Kläranlagen (Improving energy efficiency in municipal wastewater treatment plants). Texte 11/08. Dessau, Germany, Umweltbundesamt. **Forschungsbericht 205 26 307**.

Hol, A., L. Luning, L. van Dijk and A. De Man (2014). "Eerste full scale continue thermische druckhydrolyse van slib operationeel op rwzi Venlo: efficient en effectief." H2O-Online(9).

Horn, H., S. Rapp-Fiegle, W. Günthert, M. S. Holtroff, F. Bischof and M. Chwistek (2009). Schlussbericht Foschungsvorhaben "Kläranlage der Zukunft" - Themenbereiche Faulgsproduktion, Anaerobtechnik und Deammonifikation.

Hüer, L. (2015). Thermische Hydrolyse mit dem Lysotherm-Verfahren-Praxisbeispiel Kläranlage Lingen. DWA 9. Klärschlammtage 2015, Potsdam.

Hydro-Ingenieure (2013). Energieautarke Gruppenkläranlage Weilerbach.

Jenicek, P., C. A. Celis, L. Krayzelova, N. Anferova and D. Pokorna (2014). "Improving products of anaerobic sludge digestion by microaeration." Water Sci Technol **69**(4): 803-809.

Jenicek, P., J. Kutil, O. Benes, V. Todt, J. Zabranska and M. Dohanyos (2013). "Energy self-sufficient sewage wastewater treatment plants: is optimized anaerobic sludge digestion the key?" Water Sci Technol **68**(8): 1739-1744.

Kahrs, D. and O. Hermanussen (2015). Thermisch-Chemische Hydrolyse Praxisbesipiel Kläranlage Uelzen. DWA-Klärschlammtage, DWA.

Kapp, H. (1984). Schlammfaulung mit hohem Feststoffgehalt, Stuttgarter Berichte zur Siedlungswasserwirtschaft.

Karlsson, I. (2001). Full scale plant recovering iron phosphate from sewage at Helsingborg Sweden. 2nd Int. Conf. on Recovery of Phosphates from Sewage and Animal Wastes. Holland, NL.

Kempter-Regel, B. (2010). Hochlastvergärung von Klärschlamm mit integrierter Mikrofiltration.pdf. Stuttgart, Fraunhofer-Institut für Grenzflächen- und Bioverfahrenstechnik (IGB).

Kempter-Regel, B., W. Trösch, M. Oehlke and J. Weber (2003). "Integration einer Hochlastfaulung in die herkömmliche Technik - Erste bilanzierungsergebniss der Schlammfaulung in Heidelberg." KA - Abwasser, Abfall(11/2003).

Kjaer, R., J. H. Chen, M. Djafer, C. Py and B. Nielsen (2016). Two-step digestion with continuous thermal hydrolysis to optimize sludge treatment at Marquette-lez-Lille WWTP. 2nd IWA Conference on Holistic Sludge Management, Malmö-Sweden, International Water Association.

Kjerstadius, H., J. la Cour Jansen, J. De Vrieze, S. Haghighatafshar and A. Davidsson (2013). "Hygienization of sludge through anaerobic digestion at 35, 55 and 60 degrees C." Water Sci Technol **68**(10): 2234-2239.

Knörle, U., M. Buchmüller and L. Hüer (2016). "Betriebserfahrungen mit der thermischen Schlammdesintegration auf der Kläranlage Lingen/Ems." KA - Abwasser, Abfall **63**(3): 193-201.

Kopmann, T. (2012). Klärschlammhydrolyse mit dem CAMBI-Verfahren. 26. Karlsruher Flockungstagung, Karlsruhe.

Kopmann, T. and J. Kopp (2010). Full scale continuous thermal hydrolysis of waste activated Sludge for the Improvement of Sludge Digestion and Sludge Dewatering in WWTP Geiselbullach in Germany.

Krayzelova, L., J. Bartacek, I. Díaz, D. Jeison, E. I. P. Volcke and P. Jenicek (2015). "Microaeration for hydrogen sulfide removal during anaerobic treatment: a review." Reviews in Environmental Science and Bio/Technology **14**(4): 703-725.

Krugel, S., A. Parrella, K. Ellquist and K. Hamel (2006). Five years of successful operation-a report on north americas first new temperature phased anaerobic digestion system at the western lake superior sanitary district. WEFTEC. Water Environment Foundation.

Levin, D. (2004). "Biohydrogen production: prospects and limitations to practical application." International Journal of Hydrogen Energy **29**(2): 173-185.

Lu, J., H. N. Gavala, I. V. Skiadas, Z. Mladenvoska and B. K. Ahring (2008). "Improving anaerobic sewage sludge digestion by implementation of a hyper-thermophilic prehydrolysis step." Journal of Environmetal Management **88**: 881-889.

Mergelmeyer, M. and G. Kolisch (2014). Projekt Nr. 2: Verbesserung der Klärgasnutzung, Steigerung der Energieausbeute auf kommunalen Kläranlagen.

Merz, H.-U., M. Schmickl, W. Trösch and C. Galander (1999). "Zweistufiges mesophil-therophiles Verfahren zur Schlammfaulung erstmals im großtechnischen Maßstab erprobt." KA - Abwasser, Abfall **8**.

Ministerium für Umwelt, L., Ernährung, Weinbau und Forsten Rheinland-Pfalz (2014). Umstellung von Kläranlagen auf Schlammfaulung - Energetisches und ökonomisches Optimierungspotential, Ministerium für Umwelt, Landwirtschaft, Ernährung, Weinbau und Forsten Rheinland-Pfalz.

Müller, J. (1996). Mechanischer Klärschlammaufschluss. Dr.-Ing., Technische Universität Carolo-Wilhelmina.

Nachtigall, A. (2012). "Strom aus Schlamm." Umwelt **5/2012**: 48-49.

Ndoh Rossier, M., Y. Membrez and A. Mottet (2007). Comparaison des technologies de prétraitment des boues d'épuration pour l'augmentation de la production de biogaz. Bern, Département de l'environnement, des transports, de l'énergie et de la communication DETEC, Office fédéral de l'énergie.

Neis, U., K. Nickel and A. Lunden (2008). "Improving anaerobic and aerobic degradation by ultrasonic disintegration of biomass." J Environ Sci Health A Tox Hazard Subst Environ Eng **43**(13): 1541-1545.

Nilsen, P. J. (2015). 20 Jahre Erfahrung in der Schlammbehandlung unter Einsatz der Thermodruck Hydrolyse nach dem Cambi-Verfahren Herausforderungen und Ergebnisse. 9. Klärschlammtage der DWA 15.-17.06.2015, Potsdam, DWA.

Panter, K., D. Jolis, O. E. Solheim, T. Seyffarth, T. Fjaergard and G. Sorensen (2006). "THyPAD - From Pilot to Full Scale Application at Hamar WWTP." Proc. Water Environ. Fed., WEFTEC, .(9): 429–437.

Parravicini, V., E. Smidt, K. Svardal and H. Kroiss (2006). "Evaluating the stabilisation degree of digested sewage sludge: investigations at four municipal wastewater treatment plants." Water Sci Technol **53**(8): 81-90.

Pervin, H. M., P. G. Dennis, H. J. Lim, G. W. Tyson, D. J. Batstone and P. L. Bond (2013). "Drivers of microbial community composition in mesophilic and thermophilic temperature-phased anaerobic digestion pre-treatment reactors." Water Research **47**(19): 7098-7108.

Porpatham, E., A. Ramesh and B. Nagalingam (2007). "Effect of hydrogen addition on the performance of a biogas fuelled spark ignition engine." International Journal of Hydrogen Energy **32**(12): 2057-2065.

Rabinowitz, B. and R. Stephenson (2006). Effect of Microsludge on anaerobic digester performance and residuals dewatering at LA County's JWPCP, Water Environment Foundation.

Recktenwald, M., J. Wawrzynczyk, E. S. Dey and O. Norrlow (2008). "Enhanced efficiency of industrial-scale anaerobic digestion by the addition of glycosidic enzymes." J Environ Sci Health A Tox Hazard Subst Environ Eng **43**(13): 1536-1540.

Remy, C. (2012). LCA study of sludge treatment line in WWTP Berlin-Waßmannsdorf. Berlin, Kompetenzzentrum Wasser Berlin.

Ros, M. and G. D. Zupancic (2004). "Two-Stage thermophilic Anaerobic-Aerobic Digestion of Waste-Activated Sludge." Environmental Engineering Science **21**(5): 617-626.

Rosenwinkel, K.-H. (2015). Anaerobtechnik, Springer.

Rossol, D., K.-G. Schmelz and H. Meyer (2005). "Schlammfaulung bei erhöhten Temperaturen." KA - Abwasser, Abfall **52**(10): 1120-1125.

Roxburgh, R., R. Sieger, B. Johnson, B. Rabinowitz, S. Goodwin, G. Crawford and G. Daigger (2006). Sludge minimization technologies doing more to get less. WEFTEC, Water Environment Foundation.

Schmelz, K.-G. and J. Müller (2004). "Klärschlammdesintegration zur Verbesserung der Faulung - Ergebnisse großtechnischer Parallelversuche." KA - Abwasser, Abfall **51**(6):

632-342.

Sieger, R. and P. Brady (2004). High Performance Anaerobic Digestion, Water Environment Federation, Residuals and Biosolids Committee, Bioenergy Technology Subcommittee.

Sievers, M., T. I. Onyeche, F. Taetz and S. Schäfer (2006). "Niederdruckhomogenisierung für hohe Faulgasausbeuten." GWF Wasser Abwasser **147**(1): 29-39.

Song, Y. C., S. J. Kwon and J. H. Woo (2004). "Mesophilic and thermophilic temperature co-phase anaerobic digestion compared with single-stage mesophilic- and thermophilic digestion of sewage sludge." Water Research **38**(7): 1653-1662.

Stephenson, R. J. and H. Dhaliwal (2000). Method of Liquefying Microorganisms Derived from Wastewater Treatment Processes. USA. **US Patent No. 6,013,183**.

Thomé-Kozmiensky, K. J. (1998). Klärschlammentsorgung - Enzyklopädie der Kreislaufwirtschaft. Neuruppin, TK Verlag.

Tomei, M. C., N. A. Carozza and D. Mosca Angelucci (2015). "Post-aerobic digestion of waste sludge: performance analysis and modelling of nitrogen fate under alternating aeration." International Journal of Environmental Science and Technology **13**(1): 21-30.

Torres, L. G. and E. R. Bandala (2014). Energy and Environment Nowadays. New York, Nova Science Publisher.

Wang, F., T. Hidaka, T. Uchida and J. Tsumori (2014). "Thermophilic anaerobic digestion of sewage sludge with high solids content." Water Sci Technol **69**(9): 1949-1955.

Weber, J., A. Fuchs, W. Trösch and B. Kempter-Regel (2002). Energie- und Kosteneinsparung durch den Einsatz einer Hochleistungsfaulung mit Nachweis der Übertragbarkeit auf andere Kommunen und Kläranlagen, Abwasserzweckverband Heidelberg.

Willis, J. and P. Schafer (2006). Advances in thermophilic anaerobic digestion. WEFTEC, Water Environment Foundation.

Winter, A. (2003). Desintegrationverfahren zur Intensivierung der Schlammfaulung, Institut für Siedlungswasserwirtschaft Technische Universität Braunschweig. **Heft 70**.

Wolff, H.-J., K. Nickel, A. Houy, A. Lunden and U. Neis (2009). "Intensivierung der anaeroben Schlammstabilisierung mit Ultraschall." KA - Abwasser, Abfall **56**(5): 492-498.

Zábranská, J., M. Dohanyos, P. Jenicek and J. Kutil (2006). "Disintegration of excess activated sludge - evaluation and experience of full scale applications." Water Science and Technology **53**(12): 229-236.