THERMAL HYDROLYSIS TO ENHANCE ENERGETIC POTENTIAL OF SEWAGE SLUDGE: A REVIEW

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Sewage sludge biomass is a renewable energy source commonly produced by anaerobic digestion (AD). However, the limited biodegradability of sewage sludge causes a poor energy conversion of organic material into biogas and requires further enhancement. One possible solution is sludge disintegration by a thermal hydrolysis process (THP) that has already proven to enhance biogas production and improve the quality of digested sludge. This article reviews possible THP configurations, such as THP-AD, ITHP, and PAD-THP, together with different input materials and their impact on the energy balance of the wastewater treatment plant (WWTP). Data from full-scale THP demonstrate differences between the configurations and input material. Moreover, the general advantages and disadvantages of THP integration are summarized and presented as a multi-criteria analysis that simplifies the decision-making whether the THP should be integrated in the WWTP.

Key words: Biogas production; dewaterability; energy balance; sludge disintegration; thermal hydrolysis

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1. Introduction

As the amount of wastewater treated by biological processes grows globally, so does the production of the treatment by-products such as sewage sludge. Sewage sludge solids contain between 70−80% organic matter, which can be transformed into energy on a renewable basis. At WWTP, this transformation is commonly achieved by anaerobic digestion, where biogas is produced, with a methane content between 55−70%. However, sewage sludge is mainly composed of microbial and exopolymeric substances that are relatively recalcitrant to hydrolysis, the critical limiting step of the AD process. Thus, the transformation of organic matter into biogas typically achieves an efficiency of about 50% only and requires large digesters because of the long retention time [1]. The rate and effectiveness of hydrolysis can be improved by biomass disintegration using mechanical, chemical, biological, or thermal interventions [1].

Thermal hydrolysis process is a promising method for sludge disintegration. The first study on the thermal hydrolysis of sludge was published in 1972 in connection with the improvement of sludge dewaterability. In the late 1980s, exposure to sludge at high temperatures was found to improve its biodegradability. There are currently more than 80 full-scale implementations worldwide [2] that have shown that with optimization of operating parameters, it is possible to achieve higher biogas production (15−60%), better sludge dewaterability (3−9 %), and pathogen-free biosolids. THP also enables the operation of anaerobic digestion with significantly smaller volume and shorter retention times [2-6].

During THP, the cell walls of microorganisms in waste activated sludge (WAS) are ruptured, which releases the cell content (lysate). Simultaneously, the complex extracellular polymeric substances (EPS) are degraded. This results in sludge solubilization and increases the rate of hydrolysis, thereby increasing the efficiency and rate of AD. Furthermore, THP can also improve the properties of digested sludge in terms of dewaterability and hygienic quality. First, the improved dewaterability reduces the final sludge weight, leading to savings in sludge transport, disposal, and valorization. Second, the lower moisture content also improves the energy balance of sludge drying and incineration. Third, improved hygienic sludge quality improves sludge disposal, especially on agricultural land. In sum, THP provides significant benefits towards WWTP energy self-sufficiency and towards energy and material reuse of sludge, which stimulates a growing global interest in the application of THP. This article summarizes the main technological aspects of THP along with its integration possibilities into sludge processing technology. We discuss full-scale operation experiences with THP and evaluate its contribution to the energy balance of WWTP. Finally, the overall advantages and disadvantages are summarized, and different sludge management scenarios are introduced.

2. Thermal hydrolysis - process description

2.1. THP conditions

Thermal hydrolysis is one of the disintegration methods that, through heat and subsequent sudden release of pressure, disrupts the chemical bonds of the cell wall and membrane and solubilizes the cell components. This leads to a significant destruction of the sludge structure and the release of organic material. At the same time, high-molecular substances are converted into low-molecular substances [7].

In terms of operational parameters, the temperature was determined as the most influential THP parameter; even slight changes significantly impact sludge biodegradability in the subsequent AD [2]. Thus, despite the

worldwide commercialization, the optimal THP operating temperature was not determined. As stated by Devos, Haddad [2], it depends upon the quality of the sludge and multiple parameters that should be carried out on a case-by-case basis. Secondly, retention time is considered to influence the efficiency of hydrolysis, which is closely connected to enhanced biogas production; however, the optimal retention time is also case-specific. Currently, 30 minutes is the most commonly applied retention time [8]. Nevertheless, the differences in sludge composition as well as differences in WWT technology and sewage systems result in noticeable variations in biogas production and dewaterability performance and need to be further investigated [8]. Finally, it is necessary to select such a configuration and input material that meets the operating conditions of the WWTP and legislative requirements for further use or disposal of the sludge.

Due to the complex composition of the sludge, the process kinetics of thermal hydrolysis have been only partially described, but some models focus on the main components of sewage sludge: soluble evaporative matter and soluble non-evaporative matter [9]. If we focus on the largest component of sludge suspension, which is water, we find that at temperatures around 160−180 ° C and pressure around 8 bar, we are in the so-called subcritical region, which increases the solubility of hydrophobic organic substances, for example, free fatty acids. The increased density of water in the subcritical zone, together with the high dissociation constant, favors ionic reactions such as dehydration/decarboxylation of carbohydrates and alcohols. Under subcritical conditions, radical reactions leading to gasification predominate [9, 10]. Imbierowicz and Chacuk [11] published a kinetic model that examines the hydrolysis of excess activated sludge at temperatures between 150−250 °C and further divides it into two parallel reactions. The first is the thermal destruction of sludge particles associated with the transition of organic matter from undissolved to dissolved. The second parallel reaction forms a new insoluble solid phase that could be further decomposed. Other studies focus on the formation of difficult-to-decompose substances. Typically, these non-degradable organic compounds are the products of the Maillard reaction. In this process, carbohydrates and amino acids react to form compounds that contain brown pigments and are known as melanoidins [12]. It is now known that the sludge liquor is colored brown after anaerobic stabilization of the hydrolyzed sludge. This coloration can also be found in the WWTP effluent [13]. However, it is believed that not only melanoidins, but also other non-degradable organic nitrogen compounds are behind the coloration. It is further believed that these compounds are formed especially at higher temperature in THP and may have an inhibitory effect on anaerobic fermentation [12].

2.2. Integration of thermal hydrolysis in a sludge treatment line

The integration of THP into a sludge treatment line can achieve many different goals, depending on the input material and positioning of the THP in sludge processing technology. Theoretically, there are four possibilities for input materials: (I) Mixed sludge, (II) only waste activated sludge, (III) only primary sludge, and (IV) digested sludge. Practically, only three of them are applied: (I) mixed sludge, (II) only WAS, and (IV) digested sludge. The positioning of the THP is possible before anaerobic digestion (THP-AD), between two anaerobic digesters (ITHP), and after anaerobic digestion (PAD-THP). All the alternatives mentioned above can be operated in a batch mode or a continuous mode of operation.

2.2.1 Input material

THP is typically used for hydrolysis of mixed sludge (primary sludge and waste activated sludge), or only waste activated sludge (WAS). Anaerobically digested sludge after first stage AD is hydrolyzed in ITHP and fully digested sludge is hydrolyzed inPAD-THP only sporadically. Conversely, primary sludge (PS) is easily biodegradable because of the higher content of lipids and fibers and lower content of microorganisms cells compared to WAS. Therefore THP processing only PS does not provide meaningful improvements [13]. Typical characteristics of different sludges are compared in Table 1.

Activated sludge is more suitable to undergo thermal hydrolysis as its main limitations for AD are (I) high viscosity and (II) lower calorific value. The viscosity of activated sludge is linked to the high content of EPS, up to 130 $mg.g^{-1}$ suspended solids. The EPS retain water, and their destruction contributes significantly to better sludge dewaterability. Destruction of the EPS as well as cell rupture results in the organic material release that can be more easily degraded during AD. Additionally, losing the gel-like structure of WAS enables higher loading rates, while the energy demand for mixing and pumping does not increase. Lower calorific value is connected to higher water-retaining properties and lower protein content; therefore, the WAS has approximately half the energy content of PS. On the other hand, Wilson and Novak [14] confirmed that more ammonia was released from WAS than from PS after thermal hydrolysis and correlated this finding to overall higher protein content. This can be dangerous because a high concentration of free ammonia (NH_3) causes the inhibition of methanogenic microorganisms. It was reported that the methanogenic inhibition in AD could be prevented by lowering the loading rates. Furthermore, Higgins, Beightol [15] also mention the possibility of acclimatization of the biological population to higher ammonia concentration with retention times higher than 18 days in AD.

The configuration where only WAS sludge (Figure 1) is hydrolyzed is more suitable for WWTP where PS and WAS is thickened separately as the integration will not require additional process changes. The WAS is initially thickened, then hydrolyzed in THP, and finally mixed with the primary sludge. This configuration reuses heat for preheating the primary sludge and does not require dilution ahead of AD. The total amount of sludge

that is heated up to the temperatures required by THP is dramatically reduced, thus significantly reducing the energy demand. At the same time, this method does not show significant changes in the achieved results (biogas production, dewaterability) compared to THP-AD of mixed sludge [13, 16]. The most significant drawback of hydrolyzing only WAS is that the pathogen-free digested sludge cannot be guaranteed and is therefore not suitable if the direct application of sludge on agricultural land is considered.

Thermal hydrolysis of mixed sludge (Figure 2) combines advantages and disadvantages of PS and WAS discussed above. Mixed sludge is typically thickened to 15−20% dry solids (DS), reducing the energy required for heating the water. Integration of thermal hydrolysis of mixed sludge is suitable for WWTP where accumulation of PS and WAS is not separated and it is not necessary to make significant modifications. However, its biggest disadvantage compared to other configurations is its parasitic energy demand caused by heating of all sludges and subsequent cooling before entering AD [13, 16].

Finally, also digested sludge can be hydrolyzed because it still contains hydrolyzable organic matter. There are two possible configurations where digested sludge is hydrolyzed; the first is the intermediate THP (ITHP) where THP is integrated between two stages of AD, and the second is the hydrolysis of digested also known as post-anaerobic digestion thermal hydrolysis (PAD-THP), where the output of AD is hydrolyzed. Thermal hydrolysis of digested sludge is further decomposing the sludge that has already undergone the fermentation process. This type of THP further increases the solubilization and the release of readily degradable organic matter to the liquid phase, and therefore increases the degradable organic substrate for AD if liquor is returned [17]. The most significant advantage of thermal hydrolysis of digested sludge remains the hygienized end-product that meets the regulations for sludge reuse in agriculture, for example, direct application on farmland.

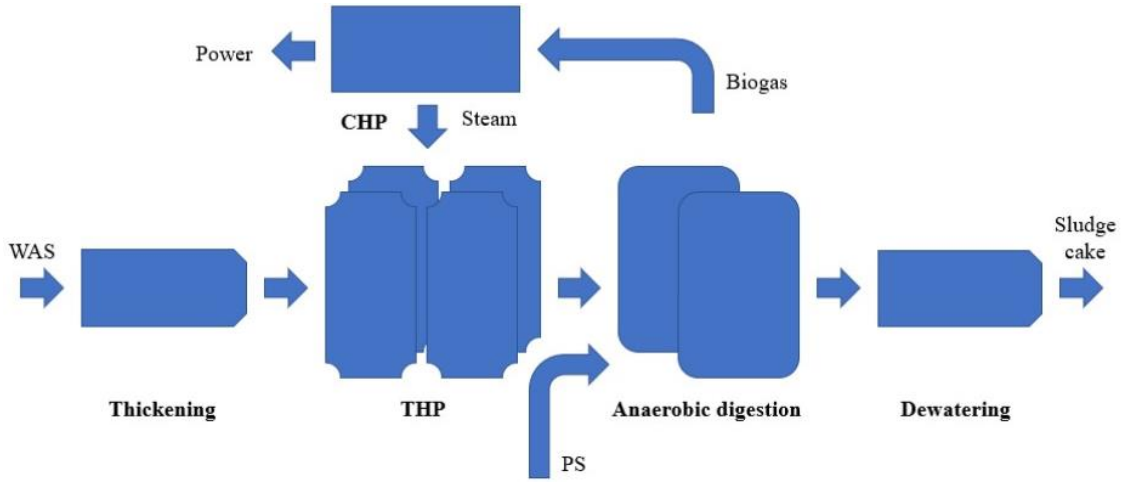

Fig 1 Integration of thermal hydrolysis process in sludge processing technology. Thermal hydrolysis of only waste activated sludge (WAS), while primary sludge (PS) is thickened and further added to hydrolyzed WAS before entering anaerobic digestion.

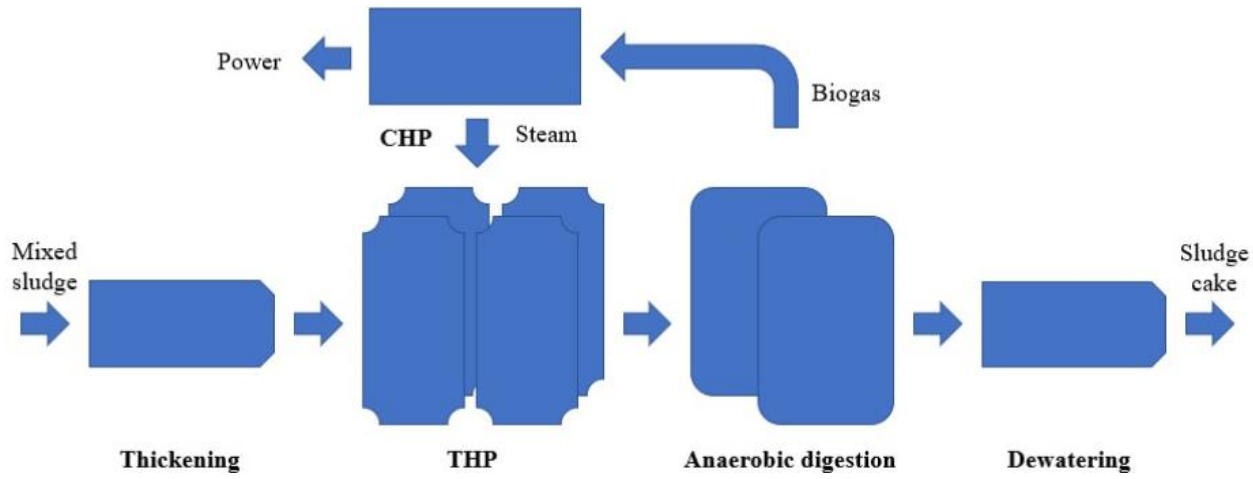

Fig 2 Integration of thermal hydrolysis process in sludge processing technology. Thermal hydrolysis of mixed sludge.

Table 1 Typical sludge characteristics (adapted from [18])

	PS	WAS	Mixed sludge	Digested sludge
Dry solids (DS), g.l^{-1}	12	7	10	30
Volatile dry solids (VDS), % DS	65	77	72	50
C, % VDS	51.5	53	51	49
H, % VDS	7	6.7	7.4	7.7
O, % VDS	35.5	33	33	35
N, % VDS	4.5	6.3	7.1	6.2
Fat, % DS	18	10	14	10
Protein, % DS	24	34	30	18
Fibers, % DS	16	10	13	10
Calorific value, kWh.t^{-1}	4200	4800	4600	3000

2.2.2 Positioning of the THP within sludge management

THP as a pretreatment method (THP-AD) is positioned upstream anaerobic digestion. Sludge is first thickened to 10−18% before entering the thermal hydrolysis to save the energy required to heat the sludge in the THP reactor. The sludge is then heated up to the operating temperature (160−180°C) by direct steam injection or heat exchangers [13]. After hydrolysis (30 min), the pressure is suddenly released, further disintegrating the sludge. The heat from the pressure release tank can be used in the form of steam for recuperative preheating of the sludge before entering the THP reactor. After cooling, the sludge is pumped into the digester. This configuration is considered as a standard THP as it is the most commonly installed. The following companies have also successfully commercialized the THP: Cambi, Veolia Water, Haarslev, Sustec, and Eliquo Water [8]. Cambi is the leading company in this regard, with more than 60 full-scale applications worldwide using mixed sludge and secondary sludge as feedstock. This configuration is more suitable for standard sludge processing lines (one-stage mesophilic anaerobic digestion) or if sludge line capacity expansion is considered.

Intermediate thermal hydrolysis (ITHP) (Figure 3) is a configuration where the mixed sludge is initially digested in the first stage AD digester, then thickened, hydrolyzed, and finally digested in the second AD. ITHP is associated with the need for major modifications to the entire sludge line and is suitable if the sludge line has excess stabilization tanks available due to the intensification of the process or if there is already a two-stage anaerobic stabilization at the WWTP. According to Zhou, Meshref [16], the ITHP achieves the best energy balance. Post-anaerobic digestion thermal hydrolysis (PAD-THP) (Figure 4) as well as in ITHP hydrolyzes already anaerobically stabilized sludge. The sludge is dewatered, and the centrate is pumped back into the AD. In contrast to THP-AD, the PAD-THP is associated with higher operating costs, leading to a higher price of the sludge treated this way. At the same time, it is necessary not to forget the possible odor arising during the heat treatment of stabilized sludge during operation [16]. This configuration also requires more digestion capacity; the AD must handle high ammonia loadings and a higher organic loading rate than THP-AD because of the returned liquor. Finally, this configuration is known more from the laboratory scale environment. So far, the only application in Germany (Amperverband) has been described by the producer. The biosolids treated this way are pathogen-free dewatered to high extent, and therefore a high level of flexibility is possible regarding final use of sludge [13].

3. Full-scale application

Several companies (Table 2) reported their THP technology. THP is in full-scale operated mostly as a batch system (CambiTHP^{TM}, Biothelys^{TM}); less common applications are continuous (Exelys^{TM}, Turbotec®, Lysotherm®, Haarslev^{TM}) and semi-continuous (HCHS) [2, 19]. SolidStream® is a patented Cambi PAD-THP.

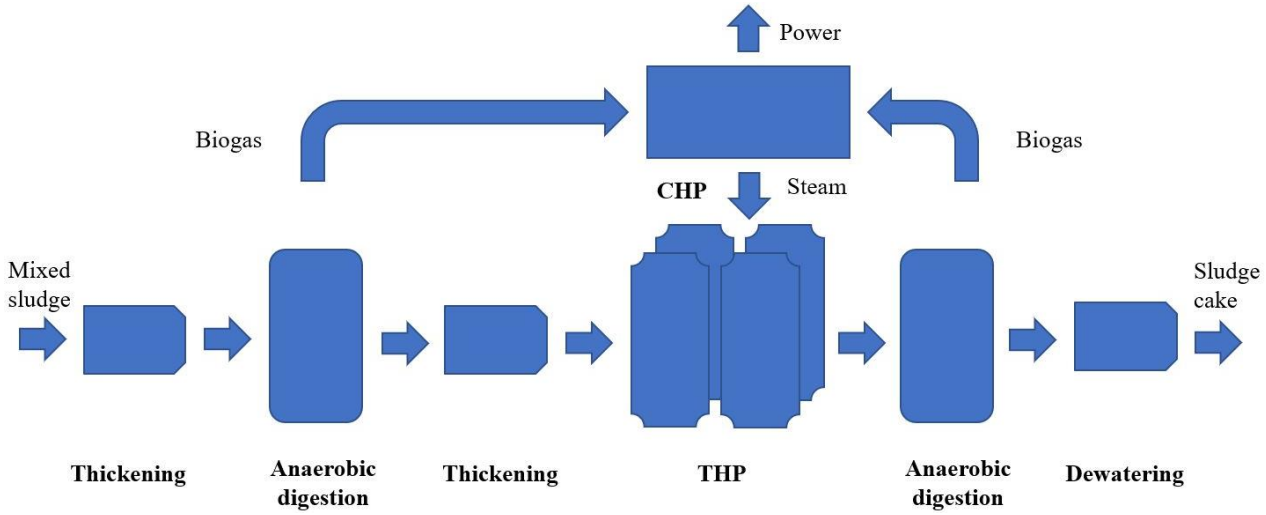

Fig 3 Integration of intermediate thermal hydrolysis process (ITHP) in sludge processing technology. Mixed sludge is first stabilized in the first anaerobic digester, then hydrolyzed in ITHP and then digested again in the second digester.

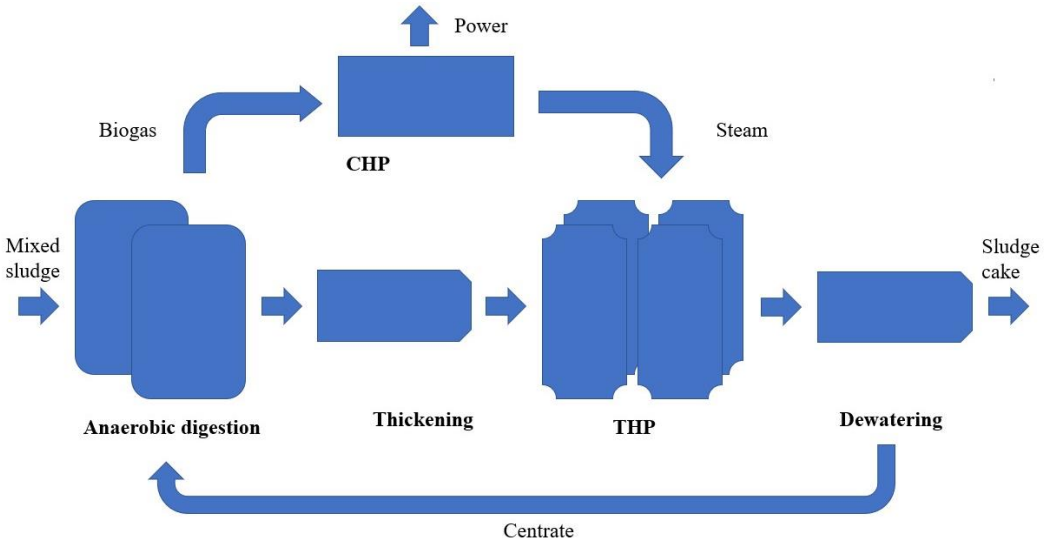

Fig 4 Integration of post-anaerobic digestion thermal hydrolysis (PAD-THP) in sludge processing technology. Mixed sludge is first digested, then dewatered, hydrolyzed, and then dewatered again.

3.1. CambiTHP™

CambiTHP™ is the world's most often-applied commercial THP technology, developed around 25 years ago. According to Volschan Junior, de Almeida [20], this technology has been installed on 51 facilities in 19 states. Company Cambi offers all configurations described in Chapter 2.3 (except the continuous operation). Processing capacity is from 1500−32000 t dry solids (DS) a year for a single process train. The batch reactors vary in their capacity from 2−12 m^3, installed in 2−4 trains if continuous feeding is required [21]. Europe's largest THP at Davyhulme processes 121000 t DS sludge in a year with 20 THP reactors (4 streams, five reactors each) and eight mesophilic anaerobic digesters. Sludge fed to THP is gathered via two routes, one with 25% DS, which is the liquid sludge directly from WWTP and is initially centrifuged and then stored in a silo. The second sludge cake is imported from seven facilities operated by United Utilities with the DS between 18−32% and stored in 2 storage silos [22]. The sludge is transferred from silos and diluted to 16.5 % DS using heated final effluent. Preheated sludge is fed to one of four THPs. Heating up to 165 °C is provided by steam injection, and the reaction period is set for 30 minutes. Afterwards, the sludge is released into a flash tank, where it is cooled down (42−44°C), diluted (8−12%), and fed into one of two 7500m^3 digesters with the maximum organic loading rate of 4.16 kg volatile solids (VS).m^{-3} digester volume per day. The digested sludge is then dewatered to more than 28% DS by centrifugation and conveyed into storage silos before being exported by trucks [22]. Centrate from thickening is fed directly ahead the sewage works. The centrate from dewatering is treated in a dissolved air flotation unit and then returned ahead the sewage works [22].

Fig 5 Picture of CambiTHP™ in WWTP Brisbane

Table 2 Commercially available thermal hydrolysis technologies and their evaluation – adapted from [23]

Company	Technology	Temperature (°C)	Time (min)	Steam explosion	Heat exchanger	Pumping
Cambi	THP	165	30	YES	NO	YES
Veolia	Excelys	165	30	NO	YES	YES
SH+H	Lysotherm	165	30	NO	YES	YES
Sustec	Turbotec	165	30	NO	YES	YES
Haarslev	ACH	165	20	YES	NO	NO
Aqualogy	Aqualysis	170	15	YES	NO	YES
teCH4+	teH4+	220	<5	YES (twice)	NO	NO

Produced biogas is stored in two gas holders and then fed to 5 combined heat and power production (CHP) engines on-site with a maximum installed power of 12 MW. The heating of the sludge in the THP reactor is partly provided by CHP waste heat, so an additional steam boiler is required. Steam boiler can be operated with biogas or auxiliary fuel source [22]. In 2015, a biogas upgrading unit was installed with a processing capacity of 900 $m^3.h^{-1}$, gas is upgraded to biomethane and sent to the natural gas grid [13]. After 135 days, run-up operation (commissioning period) results showed an increase in methane concentration in biogas by 5% (from 55% to 60%) and an increase in ammonia nitrogen load from 800 $mg.L^{-1}$ up to 2500 $mg.L^{-1}$ for hydrolyzed sludge. The loading rates for AD were increased from 1.2 $kgVS.m^{-3}$ a day to 4.16 $kgVS.m^{-3}$ a day for thermally hydrolyzed sludge. It was also stated that the monitoring of methane concentration is the most suitable parameter for monitoring of changes in the digesters [22].

Since 2014, the digester throughput increased from 68000 t DS up to 84000 t DS per year, and with investment into biogas clean up, the energy production increased from 45 GW up to 58 GW per year. It was also stated that the operation of THP is not complicated if key parameters as DS are kept within tolerance and regular maintenance is done, the performance of THP is stable and sustainable over a long time period. It was also recommended to perform regular maintenance inspections weekly. Existing digesters' performance is shown in Table 3.

Table 3 Davyhulme - typical performance (data adapted from [13])

Parameter	Value with THP	Units
Gas yield	400− 450	$m3.t^{-1}$ DS
Methane	60−62	%
H_2S	30−60	ppm
Volatile solids destruction	58	%
Digester DS	6.4	%
Ammonia	2583	$mg.L^{-1}$
pH	7.73	
VFA	600−800	$mg.L^{-1}$
Alkalinity	5000−10000	$mg.L^{-1}$
Retention time	14−24	days
DS after dewatering	30−32	%

3.2. Exelys™

The first full-scale continuous ITHP installation has been in operation in Denmark (Hillerød) in 2010. Unlike Cambi's batch system design, Exelys™ is continuous thermal hydrolysis integrated between two AD reactors. Before entering the THP reactor itself, the sludge is concentrated to 25% DS and temporarily stored in an intermediate storage tank. The steam to heat the sludge is continuously injected into the reactor through injection nozzles. As the mixture of sludge and steam moves up in the steam condenser section, the steam condenses onto the sludge, transferring the heat to the sludge, constantly raising its temperature. The heated sludge passes through a self-cleaning static mixer, which homogenizes the sludge and at the same time retains steam in the system.

The sludge with the required temperature (150°C) and pressure (9 bar) then enters the thermal hydrolysis reactor itself, where it slowly flows for about 30 minutes. The cooling of the sludge to the operating temperature of the second digester, behind THP (AD2), takes place in a heat exchanger where the energy is reused to preheat the water to produce steam and produce additional thermal energy for operating buildings or heating. After the heat exchangers, treated wastewater is added to the sludge to dilute and cool the sludge to enter the AD2. At the final part of Exelys™ THP system pressure holding pump is installed. This pump ensures steady pressure in the system and can be further used for pumping the sludge into the AD2 [24, 25].

The first results presented at Hillerød WWTP are from a 12-month operation, improved the degree of degradation of organic substances by 15%. The inclusion of Exelys™ has led to a better energy balance of anaerobic stabilization, despite the gradually deteriorating quality of raw sludge. The main advantage of this technology is the high stability of the system, which was achieved mainly in the second digester after THP [24, 25]. Dewaterability of digested sludge has improved from 25% to 30% [25]. The challenges associated with the inclusion of Exelys™ technology mainly include selecting a suitable flocculant with a low content of organic compounds and operational inclusion in the sludge line [25].

3.3. Cambi SolidStream®

An attractive, innovative application of THP was used in Cambi SolidStream® technology, where the digested sludge is hydrolyzed. After dewatering the digested and hydrolyzed sludge, the liquid stream rich on soluble COD is again digested. The first commercial use of this technology was installed in Germany (Amper-Verband) in 2015. This technology hydrolyzes sludge after anaerobic stabilization of mixed sludge.

The Cambi SolidStream® has many similarities with standard CambiTHP™; thus, it was explicitly designed to handle high ash content sludges with different rheological properties. Firstly, the sludge is after digestion thickened up to 16% DS, and the centrate is sent ahead the sewage works. Thermal hydrolysis of thickened sludge follows the same schema as THP-AD (for example, CambiTHP™) with different HRT. Hydrolyzed sludge exiting the THP is afterward dewatered at temperatures around 100 °C. The highly solubilized centrate is pumped back to the digester, where it is mixed with the digester feed and further degraded into biogas. The heat required for heating this system is fully covered by cogeneration waste heat, and no auxiliary fuel is required. The dried cake varies in DS accordingly to the polymer dosage and dewatering technology used. The cake is cooled with air, which is then scrubbed to remove odors [26].

After two years of operation (2015-2017), Cambi SolidStream® achieved, on average, a high degree of degradation of organic substances (75%) and, at the same time, correspondingly higher biogas production. The biggest advantage of including PAD-THP for anaerobic stabilization remains the high degree of dewaterability, which according to Barber, Nilsen [26] ranges typically between 38−42%, which leads to a significant reduction in the total amount of sludge produced. Furthermore, the quantity of polymer used during dewatering impacts the retention time of AD, which can be shortened by a couple of days. However, this trend was not significant for AD systems with retention times of 15 to 20 days [26]. The disadvantage of this technology is the production of non-degradable organic compounds, which can also occur in the effluent from the WWTP and highest release of ammonia nitrogen from degraded sludge. Although this technology appears to be very promising, the biggest disadvantage remains its high operational complexity. Independent and correct evaluation of the technology prevents that published data comes from the manufacturer.

4. General advantages and disadvantages

Several literature sources evaluate the advantages and disadvantages of integrating thermal hydrolysis into the technological line of a wastewater treatment plant. Their assessment is often influenced by the specific conditions of treatment plants, the geographical location, but also the subjective view of the process engineer proposing this method. Also, the meaning and weight of individual advantages and disadvantages can be very different in different regions. Most authors [6, 13, 27-29] agree on the following benefits of thermal hydrolysis:

- reduced viscosity / better rheological properties of the sludge and consequently
  - less energy-intensive sludge mixing
- possibility to perform anaerobic stabilization with higher sludge concentration
- hydrolysis largely carried out before digestion with following consequences for anaerobic stabilization
  - possibility to perform anaerobic stabilization at higher organic loading rate
  - possibility to perform anaerobic stabilization with a shorter sludge retention time
  - higher anaerobic stabilization capacity
- increasing the degradability of sludge and, as a result
  - higher biogas production
  - less stabilized sludge
- better dewaterability of stabilized sludge
  - less sludge with higher calorific value
- better sludge sanitation

On the other hand, operational experience has also revealed several disadvantages brought by the incorporation of thermal hydrolysis into the technological line of the wastewater treatment plant:

- high investment costs
- higher energy consumption for sludge heating
- poorer quality of sludge liquor, especially in terms of:
  - high concentration of free ammonia, which may be an inhibitor of the anaerobic process
  - the concentration of dissolved COD, containing poorly biodegradable and colored substances
- relatively complex technology
- need for highly qualified staff

Obviously, in each case, it is necessary to consider the degree of benefit of individual advantages and the risks associated with individual disadvantages, preferably by some of the tools of multi-criteria analysis.

- It is crucial under what conditions the integration of thermal hydrolysis is considered:
- Is there a need to increase the capacity or effectiveness of anaerobic stabilization?
- Is it necessary to improve sludge sanitation?
- Is it necessary to improve the dry matter or reduce the amount of stabilized sludge?

If the answer to at least some of these questions is not unequivocally positive, it is likely that the disadvantages of incorporating thermal hydrolysis will prevail.

It is also essential to consider the end use of the sludge method. If we do not consider landfilling as an obsolete disposal variant, the most common variants are direct or indirect use of sludge in agriculture or some of the methods of further thermal processing of sludge.

For example, when using sludge in agriculture, improved sludge sanitation is very important, but it practically does not play a role in the thermal treatment of sludge. Conversely, in the thermal treatment of sludge, an improvement in dewaterability can be essential, which shifts the calorific value of the sludge to positive values, while in the use of sludge in agriculture, improved dewaterability plays a relatively small role if sludge is not transported over very long distances.

It is also essential to assess the potential problems associated with the application of thermal hydrolysis:

Risk of financing problems, availability of qualified staff, risk associated with inhibition of the anaerobic process by high concentration of undissociated ammonia, risk associated with an increase in COD in the effluent, risk associated with discoloration of the effluent, etc.

5. Energy benefits of THP

The energy benefit of the thermal hydrolysis of sludge can be evaluated according to several aspects. Above all, it is a higher biogas production, which, of course, must be evaluated together with the energy consumption for sludge heating during THP. In addition, further thermal treatment after anaerobic stabilization can contribute to the efficient energy utilization of sludge because even in the stabilized sludge, a significant amount of organic matter remains. It can be transformed into energy by combustion, pyrolysis, gasification, or other processes. The calorific value of sludge is decisive for its energy balance, which is determined primarily by its composition and degree of dewatering. Sludge treatment methods and especially the extent of sludge energy valorization play a key role in the overall energy balance of

the WWTP. It can significantly contribute to the energy self-sufficiency of the whole technology and simultaneously to a significant reduction of its carbon footprint.

5.1. Increasing biogas production

Anaerobic degradation of biomass consists of four basic steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Hydrolysis is the first degradation step in which suspended and high molecular weight substances are converted into dissolved and low molecular weight substances. Biochemical hydrolysis is performed by enzymes of strictly anaerobic and facultatively anaerobic microorganisms. Lipids are broken down into higher fatty acids, polysaccharides into monosacharides, and proteins into amino acids. Enzymatic hydrolysis is at the same time limiting the whole process of anaerobic digestion and can be substantially accelerated by sludge pretreatment, for example, by thermal hydrolysis. Disintegration methods disrupt the physical and chemical structure of sludge as well as the cellular structure of microorganisms and lyse cells [30]. The kinetics of hydrolytic decomposition during anaerobic digestion depends on the operating conditions, mainly on the temperature, and the degree of disintegration of the input material, therefore it cannot be determined in advance [31]. Thermal hydrolysis significantly contributes to the acceleration of enzymatic hydrolysis and partially replaces it.

Sludge pretreatment by thermal hydrolysis improves the accessibility of sludge particles to microorganisms and the utilization of the sludge as a substrate for their metabolism. This results in a faster and more efficient transformation of organic substances into methane and carbon dioxide.

5.2. Increasing the calorific value of stabilized sludge, reducing the energy requirements for drying

Nowadays, the digested sludge is more and more frequently further processed thermally – dried or incinerated. From an energy point of view, the dewaterability of the sludge is a crucial parameter because an improvement of the dewaterability brings a reduction of the energy requirements for drying and/or an increase of the calorific value of digested sludge as it is shown in Figure 6 and (unhydrolyzed sludge) Figure 7 (hydrolysed sludge) and Table 4. The impact of thermal hydrolysis on the calorific value of sewage sludge calculated for a 60:40 primary: activated sludge mixture is shown in Table 4. Barber [4] calculated a rather special case where the reduction of volatile solids after digestion of thermally hydrolyzed sludge is only 26.5% and maximum dewatering of 44% DS is achieved. In such a case, the calorific value of hydrolyzed and digested sludge (expressed in a wet cake of dewatered sludge) is comparable to that of raw sludge despite the much lower organic matter fraction. However, according to practical experience, this is a very exceptional case.

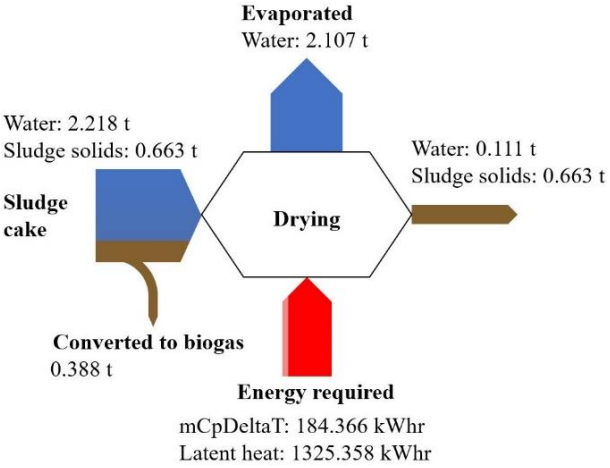

Fig 6 Sankey diagram of unhydrolyzed sludge – energy balance – overtaken from [4]

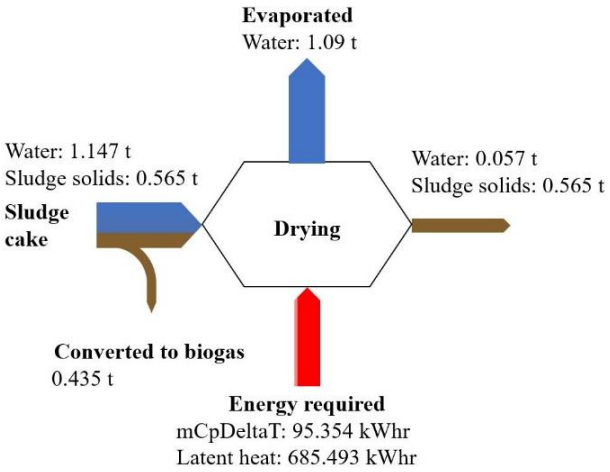

Fig 7 Sankey diagram of hydrolyzed sludge – energy balance – overtaken from [4]

Table 4 Calorific value of raw, digested, and thermally hydrolyzed sludge [4]

Sludge type	Calorific value [kJ.kg-1 DS]	Calorific value [kJ.kg-1 wet cake]
Raw	18100	4530
Digested	15000	3445
Thermally hydrolyzed and digested	13300	4385

5.3. Energy self-sufficiency of wastewater treatment and reduction of carbon footprint as a technological challenge

The energy self-sufficiency of wastewater treatment plants is one of the actual technological challenges, and some examples already prove the reality of its achievement. In such cases, it is necessary to harmonize and optimize two factors: energy consumption at the WWTP and energy production at the WWTP. Current results

show that with successful optimization of electricity consumption, it is realistic to reduce it to 20−25 per kWh.(PE.year)$^{-1}$ [32] and at the same time with successful intensification of biogas production with anaerobic sludge stabilization (e.g. THP application) to achieve electricity production from biogas at the same level.

The implementation of THP in the technological line can be one of the steps leading to the achievement of biogas production, which will be sufficient to produce electricity and heat completely covering the requirements of the entire wastewater treatment plant. Consequently, independence from external energy sources means a significant reduction in the carbon footprint of the entire wastewater treatment process.

6. Conclusions

In this review, we have demonstrated the potential of THP for the improvement of biogas yield and sludge dewaterability. The principles of THP, different input material as well as different configurations of THP were demonstrated and discussed.

The main conclusions of this reviews are:

- The THP can significantly contribute to efficient biogas production from sewage sludge that plays an essential role in achieving energy self-sufficiency in the municipal wastewater treatment process.
- Besides the biogas production improvement, the THP also benefits the further energetic use of digestate, such as better dewaterability. Better sludge dewaterability means lower content of water and significantly higher calorific value of the material.
- The optimal configuration needs to meet the requirements given by local legislation as well as the specific conditions of WWTP and geographical location.
- ITHP and PAD-THP are still showing promising operational experiences, however those methods are not established enough for their effectiveness to be objectively evaluated.
- THP-AD is on one hand an established method used worldwide as a sludge pretreatment method prior to AD. On the other hand, there are still some operating parameters that need to be further investigated.

Thus, THP is showing promising improvement of the energy balance, the most important limitation remains high investment costs. Therefore, more studies should concentrate on the economic feasibility of all THP configurations.

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