21. Thermophilic Biological Wastewater Treatment

Sindhuja Sankaran

ABSTRACT

Thermophilic treatment is one of the advanced treatment technologies used for the purification of high-strength wastewaters. Thermophilic systems are conventionally used for sludge treatment, but their ability to reduce COD to a great extent with sludge generation one-tenth when compared to the other wastewater treatment technologies, have favored its application for wastewater purification. Moreover, it operates at a rate faster than the conventional activated sludge process. Though, thermophilic process offers many benefits; the physical, chemical and biological characteristics of this process are unknown. These characteristics are so different from the conventional activated sludge process, that the knowledge based from conventional operations is unusable. As raising the temperature for treatment would not be cost-effective, thermophilic systems are best suited for industries producing high-temperature wastewater. Thermophilic wastewater treatment technologies need better understanding and research before applying it full-scale for treating wastewaters.

KEYWORDS

Thermophilic, wastewater, industrial wastewater, anaerobic, aerobic

INTRODUCTION

Thermophilic wastewater treatment refers to treatment processes purifying the wastewater coming from different sources at elevated temperatures above 45ºC to a maximum of 70ºC. The degradation of various compounds present in the wastewater is achieved by the thermophiles, which consists of mainly bacteria growing at elevated temperatures. Thermophilic treatment was traditionally used for sludge stabilization either through aerobic digestion or anaerobic digestion. Thermophilic anaerobic digestion of primary and secondary wastewater sludges has been studied since 1930, with full-scale studies beginning as early as 1931. Excellent reviews of thermophilic anaerobic digestion and thermophilic anaerobic wastewater treatment are available by Buhr and Andrews, 1977; Zinder, 1986; Parkin and Owen, 1986, and Van Lier, 1996 (Lapara and Alleman, 1999). But, in recent years more attention has been focused towards thermophilic wastewater treatment.

Thermophilic biological treatment systems represent a unique and relatively new process especially for high strength wastewater. Thermophilic wastewater treatment has several advantages compared to that of the conventional process, which includes- faster degradation rates, inactivation of pathogens, low sludge yield, process stability, etc. (Surucu et al., 1975; Lapara and Alleman, 1999; Couillard and Zhu, 1993; Rozich and Colvin, 1997), thus decreasing the detention time for treatment and thereby reducing the capital cost. They are also said to be stable under upset conditions. Another significant advantage of the thermophilic bacteria is the removal of disease causing organisms at a temperature of 55°C and above. The various benefits of the thermophilic treayment system is summarized in Table 1.

The major constrain in the biological process include the poor bacterial flocculation and foaming problems. Despite these apparent benefits, thermophilic biological treatment systems remain largely unexplored as a viable treatment technology for high strength and high temperature wastewater.

Table 1. Various Benefits of Thermophilic Wastewater Systems (Suvilampi and Rintala, 2003)

Feature	Phenomenon	Specific application
Increased rate of degradation of organics	Increased microbial growth rate and rate of diffusion of organics	Treatment can be operated with shorter hydraulic retention time (HRT) and higher volumetric loading rates (VLR)
Higher removal of specific compounds	Higher rate of chemical reactions, specific temperature-dependent enzymes	Thermophilic wastewater treatment plant can produce better effluent quality
Lower sludge yield	Higher rate of decay and maintenance energy	Cost of handling excess sludge is minimized

ANANEROBIC WASTEWATER TREATMENT

Anaerobic wastewater treatment is an attractive and generally accepted technology for the treatment of various types of medium- and high-strength wastewaters. Until recent years, this treatment technology has been mostly applied at the mesophilic temperature ranges between 25 and 40°C. Temperature has a considerable impact on various biological and physical factors of the anaerobic conversion process. For instance, the biogas production rate is reduced to a minimum at low temperatures, while it can reach extreme values under thermophilic conditions. In sludge bed systems, the biogas production rate determines the degree of mixing between the biomass and the wastewater and should, therefore, be considered in the process design. Other impacts of temperature are related to inhibition effects under thermophilic conditions. However, by adapting the process design to the expected prevailing conditions inside the reactor, the loading potentials and overall stability of the anaerobic high-rate process may be distinctly improved (Lier et al., 1997).

The anaerobic treatment of industrial wastewater has a number of potential benefits, including low energy consumption, low excess sludge production, enclosure of odors and aerosols. High rate anaerobic systems such as upflow anaerobic sludge blanket (UASB), upflow and downflow stationary packed beds, fluidized and expanded beds, have higher treatment capacity and hence low site area requirements. The upflow anaerobic filter is one of the earlier designs and its design and operational characteristics are well defined. The thermophilic digestion process, intrinsically, will have a higher activity but the process does have the reputation of being more sensitive to environmental changes than mesophilic digestion. In assessing the potential of thermophilic digesters for any specific wastewater, the main technological concerns are whether it will operate and have real advantages over a mesophilic digestion system. The direct comparisons of the performance of thermophilic and mesophilic digesters in the literature show a degree of confusion (Ahn and Forster, 2000)

Anaerobic systems are also effective in terms of energy recovery as the biogas production increases with increase in temperature. Some kinetic studies have been conducted in thermophilic conditions and comparison with the mesophilic condition has been done. Ahn and Forster (2000) studied the kinetic parameters using two anaerobic filters, treating starch wastewater at mesophilic and thermophilic condition. The results were analyzed in two ways, with a modified Stover–Kincannon model and an empirical model based on the influent COD and the hydraulic retention time. Both models were applicable to both filters and the Stover–Kincannon model showed that the thermophilic filter had a maximum COD utilization rate almost 15 times greater than the mesophilic filter. The Stover–Kincannon model was further modified to describe the methane yield. Figure 1 shows the methane production kinetics as determined by modified Stover–Kincannon model. The results also showed there was little difference between the two operational temperatures, with the Y_{max} values being 0.264 and 0.269 m3 CH_4/kg COD removed for the mesophilic and the thermophilic digester respectively. There was essentially, no difference in the maximum specific methane yields from the two filters. The results of analyzing the experimental data with the empirical model showed that, although the model described the performance of both filters well, the value of the predicted final effluent COD was very sensitive to the value of the exponent associated with the influent COD. Zhang et al., (2003) worked on bio-hydrogen production from starch wastewater under thermophilic condition (55ºC). In the study, the pH and starch loading were varied. The maximum hydrogen yield of 92 mL/g of starch added (17% of the theoretical value) was found at wastewater pH 6.0, and the maximum specific hydrogen production rate of 365 mL/ (g-VSS·d) was at wastewater pH 7.0. The methane-free biogas contained up to 60% of hydrogen. Figure 2 shows the cumulative hydrogen production from starch at thermophilic and mesophilic conditions.

Various limitations of thermophilic anaerobic wastewater treatment and its consequences in process design has been discusses by Lier (1996) in detail. The paper indicates that though thermophilic anaerobic digestion offers an attractive alternative for the treatment of medium- and high-strength wastewaters, literature reports reveal that thermophilic wastewater treatment systems are often more sensitive to environmental changes than the well-defined high-rate reactors at the mesophilic temperature range. It further suggests that a poorer effluent quality is experienced in many cases as suspended solids over in the effluent are relatively high. Another possible reason for failure of the system could be the accumulation of volatile fatty acid (VFA) compounds. Laboratory experiments reveal a relatively low sensitivity to temperature changes if high-rate reactors with immobilized biomass are used. Other results show that if a staged process is applied, thermophilic reactors can be operated for prolonged periods of time under extreme loading conditions (80-100 kg chemical oxygen demand.m-3.day-1), while the concentrations of volatile fatty acids in the effluent remain at a low level (Lier, 1996).

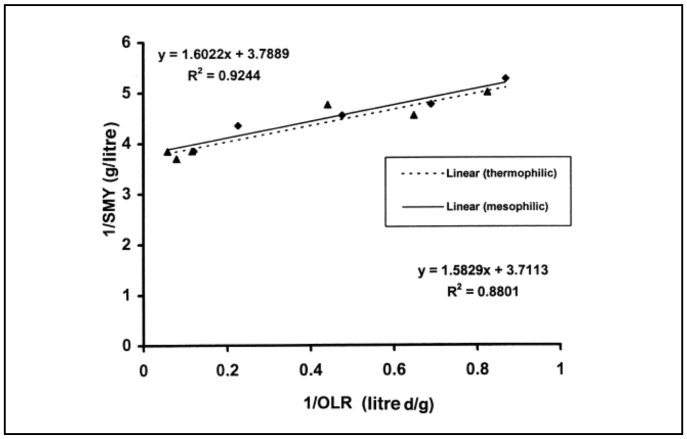


Figure 1. Determination of the Methane Production Kinetics: OLR is Organic Loading Rate in kg COD/m^3 day; SMY is Specific Methane Yield in m^3 CH_4/kg COD Removed (Ahn and Forster, 2000)

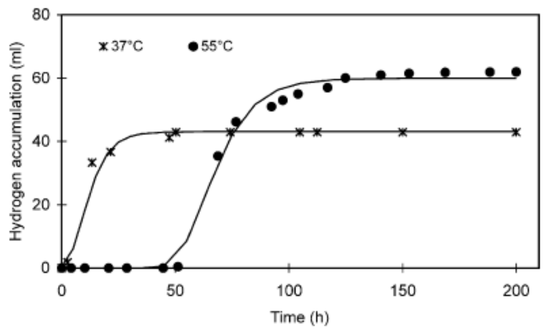


Figure 2. Cumulative Hydrogen Production from Starch at Thermophilic and Mesophilic Conditions (Zhang et al., 2003)

Many studies have been conducted in textile wastewater as the wastewater temperature is higher than wastewater from other industries (Tan, 2001). André et al., (2004) assessed the transformation and toxicity of anthraquinone dyes during thermophilic (55 °C) and mesophilic (30 °C) anaerobic treatments. In addition, the electron shuttling capacity of the redox mediator anthraquinone-2-sulfonic acid (AQS) and subsequent increase in decolorization rates were evaluated. The research objective was to find out the effect of thermophilic treatment and AQS on decolorization of the dyes. The results indicated that decolorization was better in thermophilic condition than mesophilic conditions and AQS improved the decolorization under mesophilic condition, while treating the textile wastewater. The presence of co-substrate enhanced decolorization in thermophilic conditions. The results were different when the textile wastewater was compared to the RB5 (anthraquinone dye) degradation. In RB5 decolorization, the AQS did enhance the decolorization in thermophilic condition at lower concentrations while not in mesophilic condition, in opposition to what was observed in textile wastewater. The reason for the change in decolorization rates with and without AQS with RB5 has not been mentioned or explained.

Santos et al., (2005c) studied the reductive decolorization of two azo dyes, namely: Reactive Red 2 (RR2) and Reactive Orange 14 (RO14) by the mesophilic (30°C) and thermophilic (55°C) anaerobic organisms. The aim major objective of the research was to determine the role of fermentative and methanogenic bacteria in the presence of fermentative substrate glucose and methanogenic substrate acetate, hydrogen/carbon-do-oxide, methanol and formate, in reductive decolorization of the azo dyes at mesophilic (30ºC) and thermophilic (55ºC) conditions. It was found that at 55ºC, the azo dye decolorization was much better than 30ºC. Moreover, in presence of riboflavin, the first order rate constant of the azo dye decolorization was found to be much higher than in absence of it. The dye decolorization was best in absence of both inhibitors and in presence of riboflavin at thermophilic temperatures. Santos et al. (2005a) found that in anaerobic degradation of axo dyes, both fermentative bacteria and methanogenioc archea play an important role. Moreover, The thermophilic methanogens such as *Methanothermobacter thermoautotrophicus _H* and a *Methanothermobacter*-related strain NJ1 were only able to reduce the dye in the presence of riboflavin. This suggests that anaerobic dye reduction is not a universal property among methanogenic archaea and that redox mediators may improve reductive decolorization by allowing some microbial groups commonly found in wastewater treatment systems to participate more effectively.

Lier et al., (1996) studied the thermophilic anaerobic conversion of fatty acids using dispersed and granular sludge. The range of temperature studied was from 37 to 70ºC. It was found that acetate utilization rate did not change from 50 to 65ºC, when granular sludge was utilized. Dispersed sludge showed an improved performance in comparison to granular sludge.

Many microbial communities involving thermophilic anaerobes have also been determined. *Methanothrix thermophila*-related methanogens, *Desulfotomaculum*-related bacterial populations were the key members responsible for terephthalate degradation under thermophilic methanogenic conditions in a thermophilic anaerobic hybrid reactor degrading terephthalate. *Cytophaga–Flexibacter–Bacteroides*, as well as *β-Proteobacteria*, *Planctomycetes* and *Nitrospira* were also found to degrade terephthalate under anaerobic condition (Chen et al., 2004). Phylogenetic analysis based on 16S rDNA sequences of the 72 clones developed from an anaerobic sludge treating starch wastewater at pH 6.0 showed that 85.7% of the clones were closely affiliated with genus *Thermoanaerobacterium* in family Thermoanaerobacteriaceae; the remaining 14.3% were with an uncultured *Saccharococcus* sp. clone ETV-T2 (Zhang et al., 2003). Imachi et al., (2002) found an anerobic thermophilic syntrophic propionate-oxidizing bacterium could grow fermentatively on pyruvate and fumarate in pure culture in an UASB reactor. The authors suggested that the organism may belong to *Desulfotomaculum* group, which is sulfate reducing bacterial group, gram positive and spore forming. Kengen et al., (1999) determined that thermophilic anaerobic bacteria degrading tetrachloroethene mainly belonged to genus *Dehalobacter* (90%), represented by the haloraspiring organism *Dehalobacter restrictus*, and with the genus *Desulfotomaculum* (86%). Lapara et al., (2000) found that thermophilic condition could reduce the species richness in the mixed liquor, when compared to mesophilic conditions, while analyzing the microbial community in the seven-stage reactors treating pharmaceutical wastewater in thermophilic and mesophilic condition. Additionally, they found that in thermophilic reactors, *Proteobacteria* were dominating, while the mesophilic reactors included six bacterial species: *Cytophaga-Flavobacterium-Bacteroides*, *Synergistes*, *Planctomycetes*, low-G1C gram-positives, *Holophaga-Acidobacterium*, and *Proteobacteria* (a-proteobacteria, b-proteobacteria, g-proteobacteria and d-proteobacteria subdivisions).

Yu et al., 2004 worked on break-down of difficult to degrade lignocellulosic material from paper and pulp industry under anaerobic and thermophilic condition. Anaerobic degradation consists of two major groups of organisms: the acidogens and the methanogens. The acidogens convert the organics into organic acids such as acetic, propionic, butyric and valeric acid and are more stable to the environment, while the methanogens producing methane are sensitive to environmental changes. The authors developed a hypothesis, which states that by providing a readily degradable organics, the acidogens would actively produce ethanol and organic acids, which would in-turn, enhance the hydrolysis of the lignocellulosics, thereby increasing the overall treatment efficiency. 1.9L CSTR was used to produce constant acidogenic inoculum culture for experimental runs. The temperature and pH of the reactor was maintained at 55ºC and 6.0, respectively. 125 mL serum bottles were used for the experiment. 5 mL of seed culture was added along with 95 mL of TMP wastewater. Glucose concentration was varied to determine the optimum concentration for enhancing the hydrolysis of lignocellulose. Temperature was maintained 55ºC, and initial pH was 6. In addition, thermophilic biochemical methane potential (BMP) assay were performed to evaluate overall digestibity of TMP wastewater. The VS/TS and BOD/COD ratio of TMP wastewater was 62.3% and 25.4%, respectively. Except for the recalcitrant nature of the wastewater, the wastewater did not contain significant amounts of inhibitory compounds. The inoculum culture performed well, with 99.3% organic reduction and production of short-chain organic acids, ethanol and lactate (Table 2). The authors were successful in achieving their objective. This study suggests that an alternative of using synthetic wastewater would be use of domestic wastewater for enhancing the acidogenic activity, while treating lignocellulosic material.

Table 2. Experimental Conditions and Concentrations of the Final Products in Thermophilic Acidogenic Fermentation

Batch trials	Initial glucose (g/L)	Final pH	Organic acids as acetate equivalent (mg acetate/L)	Ethanol (mg/L)	Absorbance at 280 nm (Lignocelluloses)
Control	0	5.76 (0.01)	360 (16)	43 (7)	0.020 (0.002)*
T-1	5	5.59 (0.03)	1375 (79)	687 (71)	0.057 (0.0054)
T-2	15	5.44 (0.03)	4588 (79)	1856 (132)	0.102 (0.007)
T-3	30	5.34 (0.04)	7558 (289)	3870 (144)	0.132 (0.008)

*Values in parenthesis are standard deviation

Certain studies have been conducted to compare the performance of anaerobic treatment with that of aerobic thermophilic treatment systems. Itävaara et al., (2002) studied the degradation of polylactide under aerobic and anaerobic thermophilic conditions in aquatic and solid state conditions. The results indicated that in aquatic state the degradation of the polymer was faster in aerobic condition, while in solid state condition, the anaerobic degradation was much faster than aerobic system. Thus, this study suggests that if we use suspended growth and attached growth will be suitable for aerobic and anaerobic thermophilic treatment, respectively.

Kambe et al., (1999) conducted an interesting study to determine the species involved in anaerobic thermophilic decolorization of molasses wastewater. From the taxonomical studies conducted, the strain was concluded to belong to the group *Bacillus*, resembling *B. Smithii*. The strain was effective in decolorizing 35.5% of the molasses pigment within 20 d at 55 ºC under anaerobic condition (Figure 3), while no decolorization could be observed under aerobic condition. Thus, this study reveals that anaerobic decolorization is much effective than aerobic decolorization, especially under thermophilic condition. Other organisms including fungi such as *Coriolus, Aspergillus, Rhizoctonia, Phanerochaete*, etc. are also known to degrade molasses pigment under mesophilic or thermophilic condition (Kambe et al., 1999).

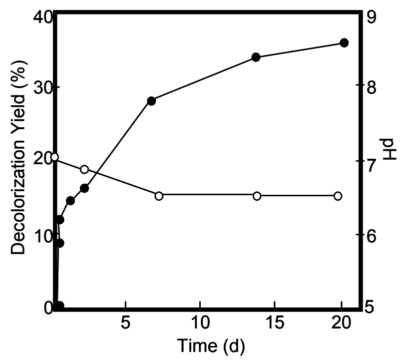


Figure 3. Time Course of the Decolorization of Molasses Pigment Strain MD-32 (Kambe et al., 1999)

Bojra et al., (1995) conducted a kinetic study on anaerobic digestion of olive mill wastewater at both mesophilic and thermophilic condition. They used a completely mixed continuous flow bioreactor to determine the kinetic parameters of mesophilic (35º) and thermophilic (55ºC) system. A constant biomass concentration of 5.45 g VSS/L was maintained in the reactor. The macroenergetic parameters were determined using Guiot's kinetic model. The yield coefficient (Y) was 0.18 and 0.06 g VSS/g COD under mesophilic and thermophilic condition, respectively. The specific rates of substrate uptake for cell maintenance were 0.12 (mesophilic) and 0.27 (thermophilic) g COD/g VSS per day. The experimental results showed the rate of substrate uptake (g COD/ g VSS per day), correlated with the concentration of biodegradable substrate (g COD/L), through an equation of the Michaelis-Menter type for the two temperatures used.

A summary of various other thermophilic anaerobic systems are summarized in Table 3.

AEROBIC WASTEWATER TREATMENT

Thermophilic systems particularly seem to be applicable for high –strength/ low flow wastewater with toxicity concerns stemming from high salinity/organic levels or presence of the hazardous compounds (Rozich and Colvin, 1997). Thermophilic aerobic treatment processes are more recent than anaerobic processes. Researchers have investigated a wide range of high-strength and/or high-temperature wastewater which includes municipal, livestock, pulp and paper, slaughterhouse, beer brewery, synthetic, citrus fruit processing, etc. It has been shown that it is also effective in a high-strength leachate, showing around 99% COD removal (Colvin et al., 1996). When Barr et al., (1996), investigated aerobic treatment of kraft pulping effluent; they found that the thermophilic treatment showed a greater COD removal at elevated temperature. In the past few years, this technology has begun to be widely used for treating various kind of wastewater even before relevant design parameters and operational requirements have been resolved (Lapara and Alleman, 1999). The major drawback of using thermophilic biological treatment systems is the poor sludge settleability. The poor bacterial settling characteristic resulting from dispersed growing microorganisms makes the biomass separation difficult and thus limiting the overall treatment efficiency of the thermophilic treatment.

Table 3. Examples of Anaerobic Thermophilic Wastewater Treatment

Wastewater	Treatment process	Operating parameters	Results	References
Distillery wastewater	Upflow anaerobic fixed-film reactor (UAFF) with Corrugated Plastic tubes and Open pore sintered glass pearls (SIRAN)	Temperature :55ºC Working Volume: 2L	UAFF + SIRAN: 84% COD removal at 12.5 kg COD/m^3.d	Perez et al., 1998
Distillery wastewater	Anaerobic fluidized bed reactor (AFB) with Corrugated Plastic tubes and SIRAN	Temperature :55ºC Working Volume: 2L	AFB + SIRAN: 96% COD removal at 5.88 kg COD/m^3.d	Perez et al., 1998
Textile wastewater (esp Azo dyes)	Sludge acclimatized in Expanded granular sludge bed (EGSB) Experiments done in batch	Effect of redox mediators was studied. Experiments done in serum bottles. Abiotic removal was also measured.	Thermophilic (55ºC) decolorization was better than mesophilic (30ºC) The redox mediators anthraquinone 2,6-disulfonate (AQDS), anthraquinone-2-sulfonate (AQS) and riboflavin increased decolorization to great extent. Thermophilic sludge did not show a lag-phase before degradation	Santos et al., 2005b
Sulphur rich paper mill wastewater	UASB and Bioassay	HRT: 6 to 2h Loading rate: 10-30 kg COD/ cu.m.d	Bioassay: 62% COD removed, with 70-80% of the removed COD being methanized. 60-74% COD removal No inhibition found	Rintala and Lepisto, 1998
Vegetable Processing high strength wastewater (derived from steam peeling and blanching of carrot, potato and swede)	UASB (Laboratory scale)	Temperature: 55ºC Loading rate was increased up to 24 kg COD m^{-3} day^{-1}	Stable thermophilic methanogenesis with about 60% COD removal was reached within 28 days. High treatment efficiency of more than 90% COD removal and concomitant methane production of 7.3 m^3 CH m^{-3} day^{-1} were achieved. Consistent to wastewater changes.	Lepisto and Rintala, 1997
Synthetic Wastewater	CSTR (Suspended) and UASB (attached)	HRT: 2 to 12h Temperatures: 35 and 55ºC	High H_2 production rates, low biomass production under thermophilic condition UASB more stable and higher hydrogen production	Gavala et al., 2005
Olive mill wastewater	Completely mixed continuous flow bioreactor	Temperatures: 35ºC and 55ºC Biomass: 5.45 g VSS/L	Thermophilic reactor works satisfactorily for HRT 10 – 40 days, the COD removal was between 94.6 – 84.4 %; while, mesophilic showed low methane production and substrate utilization in HRT 10 days.	Bojra et al., 1995

In industrial processes, where an increase in production output, may increase the need to treat greater volume of wastewater, the existing mesophilic process can be modified to face the high loading rate by upgrading a part of process to be operated at higher temperatures. Thermophilic aerobic processes are suitable for treating high-strength wastewater since the degradation rates are much higher than mesophilic conditions. But, at high temperatures, several factors as aeration, mixing, foaming and solid separation needs to be considered. Aerobic thermophilic wastewater treatments have been proved feasible in several laboratory studies, few pilot and full-scale studies (Suvilampi and Rintala, 2003). In the thermophilic treatment, both easily degradable and complex industrial wastewaters, effluent quality in terms of COD removals (total COD, CODtot and filtrated COD, CODfilt), has more often been poorer than in the effluents from analogous mesophilic processes (Suvilampi and Rintala, 2003).

Another aspect of the wastewater treatment process is the sludge yield. Sludge yield under thermophilic conditions is commonly thought to be lower than it is under mesophilic conditions. Even though increasing temperature increases microbial growth rates, the higher decay rate and increased need for maintenance energy reduce net sludge production. The ability of thermophilic microorganisms to grow at high temperatures is based on the high proportion of saturated lipids in the cell membrane. Compared to mesophiles, the longer hydrocarbon chains in the thermophilic cells increase the thermostability of the cell membrane. Thermophiles have also been reported to have larger proportions of guanine and cytosine in their DNA, which increase the melting point of the DNA molecule (Brock 1986). The various organisms identified to degrade organics under thermophilic conditions predominantly include *Bacillus* and *Proteobacteria* (Suvilampi and Rintala, 2003).

Quesnel and Nakhla, 2005 conducted a study on improving the effluent quality of thermophilically treated refractory wastewater using an aerobic biological treatment. The objective of the study was to investigate the effectiveness of activated sludge post-treatment for carbonaceous and nitrogenous contaminants removal as well as removal of specific organics, such as acetone, methyl isobutyl ketone (MIBK), toluene and *N*-nitrosodimethylamine (NDMA) from the industrial influent. The authors assessed specific VOC (acetone, toluene and MIBK) removal rather than total VOC removal. Their removal efficiency was found to be 92%, 86% and 90%, respectively. The specific VOC removal was consistent at all the stages. The NDMA removal was high and was stable with effluent concentration below discharge.

Comparison of laboratory-scale mesophilic and thermophilic activated sludge process treating diluted molasses wastewater has been some by Suvilampi et al., (2005). This study looked into various aspects of the thermophilic and mesophilic treatment processes, which included the performance in terms of COD removal, sludge settleability, sludge yield and floc sizes. Additionally, effect of Polymerized Aluminium Chloride (PAC) on the sludge settleability and effluent quality was tested. Batch experiments were also conducted to determine the feasible PAC doses and to measure mesophilic and thermophilic post-aeration effect on thermophilic effluent. A nutrient ratio of 200:5:1 for COD: N: P was used. The authors said that both the reactors were started at 20ºC, and thermophilic reactor was increased to 55ºC after a day, while mesophilic was increased from 20ºC to 35ºC after 20 days. The reason for increasing the temperature at different periods is not clear. The mesophilic reactor performed better than the thermophilic reactor. The floc size distribution was determined and found that the dominant floc size was 50- 150 µM and 150-500 µm in thermophilic and mesophilic systems, respectively. During the batch experiment on the post aeration of the thermophilic effluent, the authors found that at mesophilic aeration was good in removing the suspended, colloidal and total COD than thermophilic aeration. The soluble COD removal was better in thermophilic condition, while in mesophilic, the soluble COD increased. The authors indicate the lower removal in thermophilic condition was due to the lower diversity of the thermophilic system than the mesophilic system. PAC was added to improve the settling, but the addition of PAC neither showed any difference from non-addition nor increased the DSVI values under thermophilic condition. Authors related it to the interaction between the thermophilic floc and PAC. PAC improves the sludge properties in mesophilic condition. The sludge yield was found to be low in both mesophilic and thermophilic conditions.

As sludge settleability is a major concern in thermophilic treatment, advancement in the aerobic thermophilic treatment process have been made through the use of biofilm processes. Wastewater treatment that have biofilm growth on the surface of moving carriers within the reactor tank are called suspended carrier biofilm processes (SCBPs) or moving bed biofilm reactors (MBBRs). These processes are shown to overcome the problems as clogging, which conventional biofilm processes, such as biorotors, biofilters, trickling filters, and packed bed reactors are often reported to have (Suvilampi et al., 2003). Also these suspended carrier processes can accommodate higher organic loading than conventional mesophilic aerobic processes, such as ASPs. The rate of diffusion of organic molecules tends to increase at elevated temperatures. Apparently, an increase in temperature increases the removal rate on the carrier surface area, which may be due organics into a biofilm. Biofilm processes have been shown to be an attractive alternative to upgrade activated sludge processes, owing especially to their high loading capacity and short HRTs. Tiirola et al., (2003) worked on microbial diversity of thermophilic aerobic biofilm process using PCR amplification. They found that the bacterial diversity in suspension differed from that in the biofilm.

Volegaar et al., (2003) worked on some biokinetics to determine the degradation kinetics of acetate in a synthetic medium at mesophilic and thermophilic condition. Biokinetics of organisms in bioreactors operated in continuous and batch mode were also compared. The intrinsic maximum growth rate was found to be 1.5 time higher at 55ºC than 30ºC. The decay constants also increase from 0.004 h^{-1} to 0.017 h^{-1}, when the temperature was increased from 30 to 55ºC. The kinetic parameters are summarized in the Table 4.

Table 4. Kinetic constants of mesophilic and thermophilic biomass obtained from batch and continuous experiments. μ_{max} and k_d in h^{-1}, K_s in mg COD /L, Y and Y_{obs} in biomass COD. Acetate COD^{-1} (Volegaar et al., 2003)

Parameter	Experiment	Mesophilic (30ºC)	Thermophilic (55ºC)
μ_{max} - kd	Batch (1)	0.48	0.69
kd	Batch (2)	0.1	0.2
kd	Continuous	0.004	0.017
μ_{max} - kd	Wash-Out	0.18	0.33
K_s	Batch (3)	9	3
Y		0.50	0.49
Y_{obs}	13 h HRT	0.39	0.37
Y_{obs}	43 h HRT	0.35	0.26

A summary of various other thermophilic anaerobic systems are summarized in Table 5.

Table 5. Examples of Aerobic Thermophilic Wastewater Treatment

Wastewater	Treatment process	Operating parameters	Results	References
High-strength Oily Pet food wastewater	Aerobic MBR	HRT: 7 and 5 days Temperatures: 20º and 45ºC	Thermophilic system could handle 2 times F/M ratio of that of mesophilic condition to attain equal COD removal . Yield in thermophilic reactor was 35% of that of mesophilic condition	Kurian et al., 2005a
Pharmaceutical and petrochemical wastewater	Temperature controlled continuous reactor	Temperature raised from 30º to 65 ºC	The COD removal efficiency decreased at 55ºC for both pharmaceutical and petrochemical wastewater	Rodriguez et al., 2005
Chicken and Fish Food factory wastewater	Activated Sludge Process	Temperature: 53º to 63ºC 8.5 kg COD/m^3 per day volumetric loading rate HRT: 28.3 h	COD removal efficiency greater than 96%	Rozich and Bordacs, 2002
Newsprint whitewater	Membrane bioreactor	4 kg COD/m^3 per day volumetric loading rate HRT: 17 h	77% COD removal efficiency	Tardif and Hall, 1997
Forest Product Industrial wastewater (Volatile organic compounds)	Biotrickling filter	Temperature: 40º to 70ºC Chemicals treaded: Methanol and Pinene	Maximum methanol removal rate was 100 g/m^3 per h at 70ºC Maximum Pinene removal rate was 60 g/m^3 per h at 55ºC	Kong et al., 2001

MAJOR CONCERNS OF THERMOPHILIC TREATMENT SYSTEMS

Bioflocculation

Thermophilic treatment of industrial wastewater having a higher water temperatures, have gained more interest in recent years. The major factor limiting its application in comparison to mesophilic system is the turbid effluent, more prevalent in aerobic condition. Table 6 depicts the sludge settleability in terms of Sludge Volume Index. The reason for the effluent turbidity is that difficulties in biomass retention during thermophilic operation. Due to this, research efforts have been put in development of thermophilic membrane bioreactors and thermophilic biofilm reactors.

Table 6. Sludge Settleabilitty in thermophilic and mesophilic aerobic wastewater treatment (Suvilampi and Rintala, 2003)

Process	T (ºC)	SVI (mL/g)	Reference
ASP	35	140±70	Tripathi and Allen, 1999
	45	50±10	
	55	90±60	
	60	100±50	
ASP	35	220±160	Suvilampi and Rintala, 2002
	55	280±240	
ASP	30	21±8	Vogelaar et al, 2002
	55	12±8	
ASP after Thermophilic ASP	35	115±60	Suvilampi et al, In Press
ASP after Thermophilic SCBP	35	70±50	
ASP	55	185±85	
ASP	35	740±160	Suvilampi et al, In Press
		145±40	
	55	40±30	
		90±40	
SBR	15	110	Krishna and van Loosdrecht, 1999
	20	130	
	25	200	
	30	320	
	35	540	
SBR	30	139	Morgan and Allen, 2003
	45	340-395	
SBR with Mg^{2+}	30	45	
	45	97	

The effluent colloidal material, causing the turbidity of thermophilic bioreactors, originates from both the influent as well as from the biomass itself. Under mesophilic conditions, influent colloidal particles are effectively retained in the activated sludge flocs while under thermophilic conditions, a part is washed through. Denaturing gel gradient electrophoresis (DGGE) profiles of PCR amplified 16S DNA fragments of thermophilic reactor effluent have showed that significant amounts of thermophilic bacteria were present in the effluent as well (Vogelaar et al., 2005). Apparently, bacteria are eroded from the flocs or dispersed growing bacteria are washed out with the effluent. The absence of higher organisms in thermophilic processes could be a cause for this phenomenon. However, inhibition of the protozoa and metazoa in a mesophilic activated sludge reactor will not lead to increased turbidity levels in the mesophilic effluent when compared to the period before inhibitor addition. In all cases, a poorer retention of influent colloidal material in the thermophilic activated sludge, release of cells from the flocs and/or dispersed growth of bacteria point out that the intracellular bonding between thermophilic bacteria and other floc components is weak under thermophilic conditions, i.e. at least poorer as compared to mesophilic conditions (Vogelaar et al., 2005).

Vogelaar, et al (2005) had conducted experiments in effort to determine the reason behind the poorer flocculation under thermophilic conditions. The research was conducted on activated sludge collected from mesophilic and thermophilic lab scale plug flow reactor (4L) operated for more than 6 months at steady state and from municipal wastewater sludge to determine the factors causing diminished bioflocculation and turbid effluent under thermophilic conditions. The authors developed various hypothesis based on some literature review to determine the possible reason for diminished bioflocculation under thermophilic condition. The main focus of the paper was with respect to the colloidal particles in the wastewater and mixed liquor, which was assumed to be the major basis for poor thermophilic biological treatment. Authors state that the origin of colloidal particles can be from bioreactor biomass as well as influent. The paper focuses on certain phenomena, which includes: hydrophobic interactions measured by means of colloidal particles adsorption on the hydrophobic surface at different temperatures; effects of biomass type, biomass viability and oxygen on removal of colloidal particles with different sludge type; and variations in zeta potential, hydrophobicity, sensitivity towards shear potential and sludge particle size distribution for different types of sludge. The three types of sludge investigated were mesophilic and thermophilic sludge treating anaerobically pre-treated paper process water in plug-flow reactor, and municipal wastewater sludge.

Authors used reflectometry to measure the adsorption of colloids in the macroscopic flat surface from temperatures 20ºC to 60 ºC. Adsorption experiments revealed that the amount of colloidal particles adsorbed increased from 20ºC to 50ºC and decreased from 50ºC to 60ºC. It was interesting to note that mesophilic sludge in presence of oxygen removed 44% turbidity in effluent, while thermophilic sludge removed 10% turbidity through colloidal COD removal at 55ºC. When thermophilic sludge was applied with oxygen at 30ºC, the performance further decreased to 5%. In absence of oxygen, hardly any colloidal particles were removed. Authors concluded that it is unlikely that changes in the hydrophobic interaction with temperature are causing the large observed differences in bioflocculation behavior. Furthermore, they suggest another possible reason for poor bioflocculation in thermophilic conditions. They propose that changes in polymer interactions with temperature and/or by the interplay with exo-enzymes in the activated sludge could be another possible cause for poor thermophilic bioflocculation. Not much research has been conducted in this aspect of thermophilic treatment. The attempt of researchers to find a solution in order to overcome the draw-backs and take advantage of the thermophilic treatment is encouraging. Though there has been ongoing research in this aspect, the researchers are yet to determine the exact reason for inability to flocculate and to determine the solution for this problem.

Rise in Operating Temperature

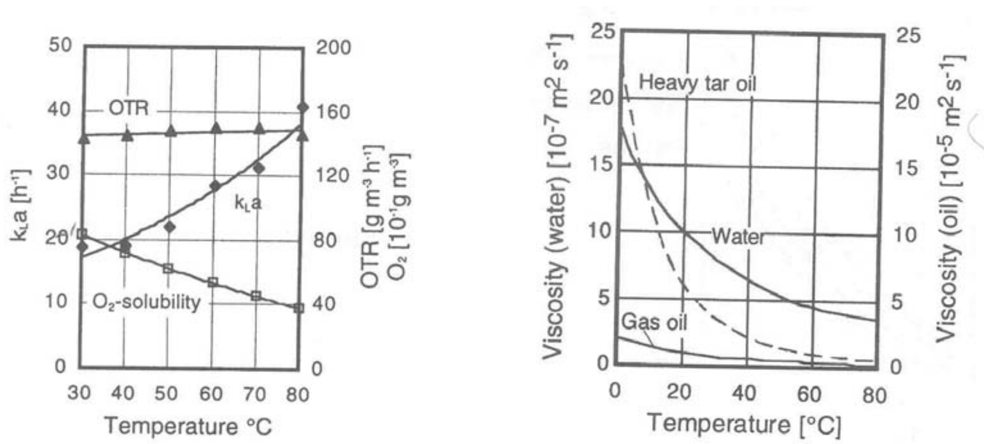
Many industrial effluents, such as those from food processing, textile industry, paper and pulp industry are often discharged at elevated temperatures. Treating these organic rich effluents under conventional mesophilic condition requires pre-cooling, and has the risk of losing the biomass activity if the cooling system breaks down. (Zhang et al., 2003). Under these circumstances, where the wastewater is present at an elevated temperature, thermophilic treatment systems are more applicable as the energy and cost required for increasing the bioreactor operating temperature is not required.

Solubility of Oxygen at Elevated Temperature

Another constrain, which is thought to affect the degradation rate in a thermophilic system is the low oxygen concentration at higher temperature. This is not found to be true. The oxygen transfer plays a more significant role in the thermophilic degradation than the oxygen solubility, thereby enhancing the degradation process (Boogerd et al., 1990). Though the solubility of oxygen decreases with increase in temperature, the oxygen transfer efficiency is much higher at elevated temperatures, thereby aiding the aerobic organisms in degradation (Figure 5a). Volegaar et al., (2000) tested the oxygen transfer efficiency (OTR) in tap water, anaerobically pre-treated paper process water and thermophilic sludge grown on mineral media and VFA as C source. The OTR was measured from 20º to 55ºC in tap and process water. The OTR was found to be almost constant in tap water at specific temperature range, while it increased in process water. The constant OTR in case of tap water was due to the counteracting effect of an increased overall oxygen transfer coefficient versus the decreased oxygen saturation concentration at higher temperatures.

Viscosity of solvents

The viscosity of the solution is an important factor in determining the wastewater treatment efficiency and also, the settleability of sludge. Though the viscosity of the water decreases with increase in temperature, the organic pollutant and the mixed liquor can behave differently (Figure 5b). It is important to study the viscosity of the mixed liquor as it may provide the information about the extra polymeric substances present, which may indirectly affect flocculation process.



(a) (b)

Figure 5 (a) Oxygen Transfer Efficiency (OTR), Oxygen Solubility and Overall Transfer efficiency (k_La at temperature T, ºC (b) Viscosity of Water, Gas Oil and Tar Oil at varying temperature (Boogerd et al., 1990).

Solubility of Hydrophobic substances

The solubility of hydrophobic complex organic compound with single or multiple benzene rings can be difficult to degrade at elevated temperature, as the aqueous solubility of these compounds is very low. Eisenschenk et al.., (2005) conducted experiments on biodegradation of poly-aromatic hydrocarbons (PAH) at elevated temperatures. They expected the degradation rate to reduce with increasing temperature due to solubility concerns. The results obtained from the study, indicted that degradation rates were much higher at elevated temperatures (Table 7). The relative solubility of the PAH compounds also increased with temperature as shown in Figure 6.

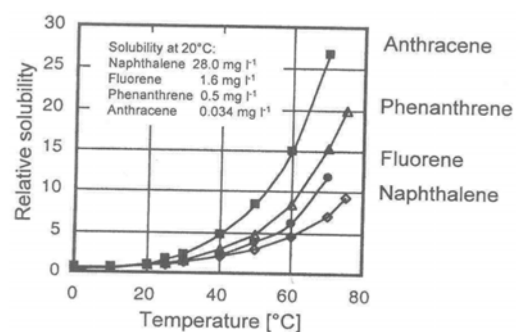


Figure 6. Solubility of PAH compounds at varying temperature (Eisenschenk et al.., 2005)

Table 7.Concentration and degradation kinetic of PAH compounds at elevated temperatures (Eisenschenk et al.., 2005)

Compound	20ºC		40ºC		60ºC	
	Conc. (ppm)	Rate Constant (min^{-1})	Conc. (ppm)	Rate Constant (min^{-1})	Conc. (ppm)	Rate Constant (min^{-1})
Fluorene	1.498	1.345E-03	3.695	2.203E-03	8.806	5.265E-03
Phenanthrene	0.902	4.329E-04	2.566	7.085E-04	6.344	4.027E-03
Fluoranthene	0.176	1.329E-04	0.596	2.056E-04	1.712	9.298E-04

Foaming

Foaming is one of the problems in thermophilic systems, especially aerobic treatment systems. The foaming problem depends mainly on the wastewater treated.

ADVANCEMENTS IN THERMOPHILIC TREATMENT SYSTEMS

Membrane Bioreactors

Thermophilic treatment system support a persistent non-flocculating bacterial community that prevents biomass separation from treated effluent by conventional sedimentation /clarification, thus limiting the application of thermophilic biological treatment system. Looking into this aspect, membrane bioreactors (MBR) could be an attractive option where sludge retention of 100% can be achieved regardless of the cell flocculation. Moreover, MBRs support extremely high levels of biocatalyst and therefore can metabolize the substrate and generate metabolic products at a much faster rate than conventional batch, fed-batch, or continuous-flow systems. In recent years, the membrane systems are also becoming more economical, which has stimulated interest in its application as an alternative operational strategy for biological wastewater treatment.

Very few studies have been conducted on thermophilic MBR wastewater treatment. When studies were conducted treatment of lactose and gelatin containing synthetic wastewater, the thermophilic aerobic treatment removed 760 mg/L COD when the cells were retained when compared to 160 mg/L without membrane filtration at 13.1 h HRT. The studies also determined the bacterial community shift within 2 days of membrane bioreactor operation. The biomass level in the bioreactor also increased significantly. Though the study indicates the improvement in the performance with presence of membrane compared to absence of it, comparison with mesophilic treatment is absent. (Lapara et al., 2001). A MBR study was conducted on oily pet food wastewater using MBR. A comparison of the thermophilic reactor was done with mesophilic systems. The authors mention that the results were contradicting to the available literature on thermophilic treatment systems, with respect to yield and food to microorganisms (F/M) ratio. The thermophilic system did not perform well, with lower biomass compared to that of mesophilic system. The major set-back of the paper was that comparison was done between two reactors of completely different configuration. Membrane bioreactor technology has been widely used to treatment industrial wastewater at mesophilic or room temperatures. But, few researchers have explored the potential of thermophilic MBR. (Suvilampi and Rintala, 2003)

Kurian, et al (2005b) investigated the treatability of high strength oily pet food wastewater using membrane-coupled bioreactors (MBR) under aerobic mesophilic and thermophilic conditions. The major objective of the study was to asses the performance of the two MBR at mesophilic (18-20ºC) and thermophilic (45ºC), in addition to verify its applicability for treating animal fat-contaminated wastewaters. The pre-treated pet food producing industry wastewater (using DAF) was used as a feed for MBR systems. The MBR influent is characterized by around 6 g/L O & G, 51 g/L COD, 16 g/L BOD and 8.3 g/L VFA. The thermophilic and mesophilic MBR differed to a great extent, which may raise doubts in the results obtained. The results indicated a large difference in the biomass concentration in the conventional (mesophilic) and thermophilic MBR systems, with VSS of 15 g/L and 2.8 g/L, respectively. The biomass increased with decrease in HRT in the mesophilic MBR, while it was vice-versa in thermophilic MBR. The authors suggest that reason for low biomass with increasing load in thermophilic MBR could be due to frequent fouling. When the HRT was decreased from 6.3 to 5 days, thermophilic effluent COD increased, while in mesophilic, it did not change. Authors suggest reason to be short retention time and escape of soluble compounds (due to higher solubility) through membrane under thermophilic condition. The authors state that the overall contribution of physical filtration for soluble COD removal was 2 %. In thermophilic effluent, 50% of the total COD was contributed by VFA. Acetic acid was predominant (34%) among the major VFA compounds. The ammonia removal in the thermophilic reactor was high than the mesophilic MBR. The F/M ratio had an effect on COD removal efficiencies in both the systems, with performances deteriorating beyond 1.1 and 0.5 g COD/g VSS d in the thermophilic and conventional MBR, respectively.

Though many studies are ongoing on thermophilic membrane treatment systems, it is uncertain whether this would provide a solution for poor Bioflocculation in thermophilic treatment systems.

Thermophilic Floc Forming Microorganism

With technological advancements, science and research, today man has reached the space. Inspite of various achievements, human race continues to make further advancements in terms of inventions and discoveries. This is also true in case of wastewater treatment technologies. Today, we face the problem of poor flocculation in thermophilic treatment systems. There have been certain studies, where good microbial flocculation was achieved under thermophilic conditions. If we can further improve these researches by isolating the thermophilic floc forming organisms, this could be a major break-through in thermophilic treatment processes.

Other Advancements

Recent studies have shown that thermophilic effluent quality can be improved by post-treatment, such as membrane filtration. The other advancements to face the poor flocculation of the thermophilic biomass could be use of chemicals to aid flocculation, such as cationic aluminum polymer. Other chemicals like Magnesium can also be tested.

CONCLUSION

Thermophilic systems present an elegant solution for the treatment of high-strength wastewaters. High degradation rates at thermophilic temperatures represent a potential advantage compared to conventional mesophilic process, though providing heat to raise the reactor temperature limits the cost effectiveness of this process. Due to the enormous energy requirement, thermophilic treatment is thought to be economically infeasible treatment process. But, this could be economically favorable for an industry which releases hot wastewater stream. Usually, the treatment process in such industries cools the wastewater to a temperature typical for conventional treatment process. If we could treat a hot wastewater stream as such under thermophilic condition without lowering the temperature much, this could be an effective option in terms of both cost and energy consumption.

REFERENCES

- Ahn, J.H; and Forster, C.F. (2000) Kinetic analyses of the operation of mesophilic and thermophilic anaerobic filters treating a simulated starch wastewater. *Process Biochem.*, **36,** 19.
- André, D.S.B.; Iemke, B.A.E.; Francisco, C.J.; and Jules, V.L.J.B. (2004) Effect of Different Redox Mediators during Thermophilic Azo Dye Reduction by Anaerobic Granular Sludge and Comparative Study of Mesophilic (30ºC) and Thermophilic (55ºC) Treatments for Decolourization of Textile Wastewaters, *Chemosphere*, **55**, 1149.
- Barr, T.A.; Taylor, J.M.; and Duff, S.J.B. (1996) Effect of HRT, SRT and Temperature on the Performance of Activated Sludge Reactors Treating Bleached Kraft Mill Effluent. *Water. Res*., **30**, 779.
- Bojra, R.; Martiqb, A.; Banks, C.J.; Alonsob, V.; and Chicab, A. (1995) a Kinetic Study of Anaerobic Digestion of Olive Mill Wastewater at Mesophilic and Thermophilic Temperatures. *Environ. Pollut.***,** **88,** 13.
- Boogerd, F.C.; Bos, P.; Kuenen, J.G.; Heijnen, J.J.; and Van der Lans, R.G.J.M. (1990) Oxygen and Carbondioxide Mass Transfer and the Aerobic, Autophilic Cultivation of Moderate and Extreme Thermophiles: A Case Study Related to the Microbial Desulfurisation of Coal. *Biotechnol. Bioengg*., **35**, 1111-1119
- Brock, T. (1986) Introduction: An Overview of the Thermophiles. In: Brock TD (Ed), Thermophiles: General, Molecular, and Applied Microbiology (pp 1–16). Wiley Series in Ecological and Applied Microbiology, Wiley-Interscience Publications, Wiley & Sons, New York.
- Chen, C.L.; Macarie, H.; Ramirez, I., Olmos, A.; Leong, S.; Monroy, O.; and Liu, W.T. (2004) Microbial Community Structure in a Thermophilic Anaerobic Hybrid Reactor Degrading Terephthalate. *Microbiol.*, **150**, 3429.
- Colvin, R.J.; Rozich, A.F.; Aco, V.; Hollerbach, G.H.; and Mitchell, D. (1996) Thermophilic Aerobic Treatment of High Strength Groundwater: Full-scale system operations. In Proceedings WEFTEC '96, Water Environmental Federation, Alexandria, VA,U.S.A.
- Couillard, D.; and Zhu, S. (1993) Thermophilic Aerobic Process for the Treatment of Slaughterhouse Effluents with Protein Recovery. *Environ. Pollut*., **79**,121.
- Eisenschenk, M.; Petersen, J.N.; and Peyton, B.M. (2005) Thermophilic Biodegradation of Polyaromatic Hydrocarbons. Washington State University, http://composites.wsu.edu/navy/Navy1/Presentations/peyton.pdf, as seen on Nov, 2005.
- Gavala, H.N.; Skiadas, I.V.; and Ahring, B.K. (2005) Biological Hydrogen Production in Suspended and Attached Growth Anaerobic Reactor Systems. *Int. J. Hydrogen En*., In Press.
- Imachi, H.; Sekiguchi, Y.; Kamagata, Y.; Hanada, S.; Ohashi, A.; & Harada, H. (2002). *Pelotomaculum thermopropionicum* gen. nov., sp. nov., an anaerobic, thermophilic, syntrophic propionate-oxidizing bacterium. *Int J Syst Evol Microbiol.,* 52, 1729.

- Itävaara, M.; Karjomaa, S.; and Selin, J.F. (2002) Biodegradation of Polylactide in Aerobic and Anaerobic Thermophilic Conditions. *Chemosphere,* **46**, 879.
- Kambe, T.N.; Shimomura, M.; Nomura, N.; Chanpornpong.; and Nakahara, T. (1999) Decolorization of Molasses Wastewater by *Bacillus* sp. under Thermophilic and Anaerobic Conditions. *J Biosci Bioeng.*, **87**, 119.
- Kengen, S. W. M.; Breidenbach, C. G.; Felske, A.; Stams, A. J. M.; Schraa, G. ; and Vos, W. M. (1999). Reductive Dechlorination of Tetrachloroethene to Cis-1,2-dichloroethene by a Thermophilic Anaerobic Enrichment Culture. *Appl Environ Microbiol.,* **65**, 2312.
- Kong, Z.; Farhana, L.; Fulthorpe, R.R.; and Allen, D.G. (2001) Treatment of Volatile Organic compounds in biotrickling Filter under Thermophilic Conditions. *Environ. Sci. Technol.* , **35**, 4347.
- Kurian, R.; Acharya. C.; Nakhla, G.; and Bassi, A. (2005a) Comparison of Conventional and Thermophilic Aerobic MBRs Treating High Strength Oily Pet Food Wastewater. In Proceedings WEFTEC '05, Water Environmental Federation, Washington D.C.,U.S.A.
- Kurian, R.; Acharya. C.; Nakhla, G.; and Bassi, A. (2005b) Conventional and Thermophilic Aerobic Treatability of High Strength Oily Pet Food Wastewater using Membrane-Coupled Bioreactors. *Water Res*., Article in Press.
- Lapara, T.M.; and Alleman, J.E. (1999) Thermophilic Aerobic Biological Wastewater Treatment. *Water Res*., **33**, 895.
- Lapara, T.M.; and Nakatsu, C.H.; Pantea, L.; and Alleman, J.E. (2000) Phylogenetic Analysis of Bacterial Communities in Mesophilic and Thermophilic Bioreactors Treating Pharmaceutical Wastewater. *Applied and Environmental Microbiology*, **66**, 3951.
- LaPara, T.M.; Konopka, A.; Nakatsu, C.H.; Alleman, J.E. (2001) Thermophilic Aerobic Treatment of a Synthetic Wastewater in a Membrane-coupled Bioreactors. *J Ind Microbiol Biotechnol*., **26**, 203.
- Lepisto,S.S.; and Rintala, J.A. (1997) Start-up and Operation of Laboratory-Scale Thermophilic Upflow Anaerobic Sludge Blanket Reactors Treating Vegetable Processing Wastewater. *J. Chem. Tech. Biotechnol.,* **68,** 331.
- Lier, J.B.V.; Rebac, S.; and Lettinga, G. (1997) High-rate Anaerobic Wastewater Treatment under Psychrophilic and Thermophilic condition. *Water Sci. Technol*., **35**, 199.
- Lier,V. J. B. (1996). Limitation of Thermophilic Anaerobic Wastewater Treatment and the Consequences for Process Design. *Antonie Van Leeuwenhoek*, **69**, 1.
- Lier,V. J.B.; Martic, J.L.S.; and Lettinga, G. (1996) Effect of temperature on the Anaerobic Thermophilic conversion of Volatile Fatty acids by Dispersed and Granular Sludge. *Water Res*., **30**, 199.
- Perez, M.; Romero, L.I.; and Sales, D. (1998) Comparative Performace of High Rate Anaerobic Thermophilic Technologies Treating Industrial Wastewater. *Water Res.* , **32**, 559.
- Quesnel, D.; and Nakhla, G. (2005) Optimization of the Aerobic Biological Treatment of Thermophilically Treated Refractory Wastewater. *J. Hazard. Mater.,* **125**, 221.
- Rintala, J.A.; and Lepisto, S.S. (1998) Thermophilic Anaerobic Treatment of Sulfur Rich Forest Industry Wastewater. *Biodegradation*, **9**, 225.
- Rodriguez, E.; Narros, A.; Molina, M.J.; and Alvarez, C. (2005) Thermophilic Aerobic Treatment of Pharmaceutical and Petrochemical wastewaters. In Proceedings WEFTEC '05, Water Environmental Federation, Washington D.C., U.S.A.
- Rozich, A.; and Bordacs, K. (2002) Use of Thermophilic Biological Aerobic Technology for Industrial Wastewater Treatment. *Wat. Sci. Technol.,* **46,** 83.
- Rozich, A.F.; and Colvin, R.J. (1997) Design and Operational Consideration for Thermophilic Aerobic Reactors Treating High Strength Wastes and Sludges. In Proceedings of the 52nd Industrial Waste Conference, Purdue University, ed. J.E. Alleman, Ann Arbor Press, Ann Arbor, MI, U.S.A.
- Santos, A.B.D.; Marta, P.M.; Bok, F.A.M.; Stams, A.J.M.; Lier, J.B.V.; and Cervantes, F.J. (2005a) The Contribution of Fermentative Bacteria and Methanogenic Archea to Azo Dye Reduction by a Thermophilic Anaerobic Constrocium. *Enzyme Microbial Technol.*, In Press.
- Santos,A.B.D.; Iemke, B.A.E.; Francisco, C.J.; and Jules, V.L.J.B. (2005 b) The Transformation and Toxicity of Anthraquinone Dyes during Thermophilic (55 °C) and Mesophilic (30 °C) Anaerobic treatments. *J Biotechnol.,* **115**, 345.
- Santos,A.B.D.; Madrid, M.P.D.; Stams, A.J.M.; Lier, J.B.V.; and Cervantes, F.J. (2005c) Azo Dye Reduction by Mesophilic and Thermophilic Anaerobic Consortia. *Biotechnol. Prog.*, **21**, 1140.
- Surucu G.A. (1975) Thermophilic Aerobic Treatment of High-Strength Wastewaters with Recovery of Protein. Ph.D. Thesis, University of Illinois, Champaign-Urbana.

- Suvilampi, J.; and Rintala, J. (2003) Thermophilic Aerobic Wastewater Treatment, Process Performance, Biomass Characteristics and Effluent Quality. *Review in Environ. Science and Biotechnol*., **2**,35.
- Suvilampi, J.; Lehtomaki, A; and Rintala, J. (2003) Comparison of Laboratory-Scale Thermophilic Biofilm and Activated Sludge Processes Integrated with a Mesophilic Activated Sludge Process. *Bioresour. Technol.*, **88,** 207.
- Suvilampi, J.; Lehtomaki, A; and Rintala, J. (2005) Comparative Study of Laboratory-scale Thermophilic and Mesophilic Activated Sludge Processes. *Water Res.*, **39**, 741.
- Tan, N.C.G. (2001) Integrated and Sequential Anaerobic/Aerobic Biodegradation of Azo Dyes. Thesis, Wageningen University Research Center, Wageningen, The Netherlands, 104 p.
- Tardif, O.; and Hall, E. (1997) Alternatives for Treating Recirculated Newsprint Whitewater at High Temperatures. *Wat. Sci. Technol.,* **35,** 57.
- Tiirola, M.A.; Suvilampi, J.E.; Kulomaa, M.S.; and Rintala, J.A. (2003) Microbial Diversity in a Thermophilic Aerobic Biofilm Process: Analysis by Length Heterogeneity PCR (LH-PCR). *Water Res.,* **37**, 2259.
- Vogelaar, J.C.T.; De Keizer, A.; Spijker,S.; and Lettinga, G. (2005) Bioflocculation of Mesophilic and Thermophilic Activated Sludge. *Water Res.*, **39**, 37.
- Volegaar, J.C.T.; Klapwijk, B.; Lier, J.B.V; and Rulkens, W.H. (2000) Temperature Effects on the Oxygen Transfer Rate Between 20º and 55ºC. W*ater Res.,* **34**, 1037.
- Volegaar, J.C.T.; Klapwijk, B.; Temmink, H.; and Lier, J.B.V (2003) Kinetic Comparison of Mesophilic and Thermophilic Aerobic Biomass. *J. Ind. Microbiol. Biotechnol*. , **30**, 81.
- Yu, Y.; Park, B.; and Hwang, S. (2004) Co-digestion of Lignocellulosics with Glucose using Thermophilic Acidogens. *Biochem. Eng. J*, **18**, 225.
- Zhang, T.; Liu, H.; and Fang, H.H.P. (2003) Biohydrogen Production from Starch in Wastewater under Thermophilic Condition*. J. Environ. Management*, **69**, 149.