Comprehensive review and compilation of pretreatments for mesophilic and thermophilic anaerobic digestion

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ABSTRACT

Organic matter hydrolysis prior to anaerobic digestion has been shown to improve biogas production (30–50%) and reduce solids (20–60%) by ultrasound, chemical, conventional heating, and microwave pretreatments. Numerous studies have been performed to determine the extent of digestion improvement but few focus on financial feasibility of these processes. A comprehensive model was created using Microsoft Excel and its Visual Basic Assistant to evaluate pretreatment permutations for conventional wastewater treatment plants. The four above-mentioned processes were evaluated for energetic and financial demands. Well-established energy equations and wastewater characteristics, both average and high, were used. Average and high flows were 460 and 750 × 10³ m³/d, respectively. Net costs per influent flow for ultrasound, chemical, conventional heating, and microwave were 0.0166, 0.0217, 0.0124, 0.0119 $/m³ and 0.0264, 0.0357, 0.0187, and 0.0162 $/m³ for average and high conditions, respectively. The average cost increase from results excluding pretreatment use for all processes was 0.003 and 0.0055 $/m³ for average and high conditions, respectively. No matter the permutation, pretreatments requiring more energy to achieve required hydrolysis levels were costlier. If energetic recoveries are substantial, dewaterability is positively affected, and solids meet environmental constraints to be handled and disposed at lower costs, pretreatments can be viable.

Key words | chemical, digestion, microwave, pretreatment, thermal, ultrasound

INTRODUCTION

Municipal wastewater treatment plants (WWTPs) using anaerobic digestion (AD) to handle primary and secondary sludge (PS, WAS) are common-place. Advantages to AD as compared to aerobic digestion are well known and include waste conversion to methane, low nutrient needs, and no oxygen requirement (Kiyohara et al. 2000). Methane production benefits sludge handling/disposal and energy demands. As populations grow and sludge land-use policies become more stringent WWTPs can experience difficulties performing within environmental and financial constraints (Pérez-Elvira et al. 2006).

Hydrolysis of organic matter is considered to be the rate-limiting step in WAS degradation. Where WWTPs have disproportionately high sludge handling/disposal costs, treat wastes of low biodegradability, and/or generate minimal daily biogas, pre-treatments (PTs) can be incorporated as sustainable improvements (Benabdallah El-Hadj et al. 2007)). Such PTs include mechanical, thermal, chemical, biological, and combinations of them (Toreci et al. 2007). PTs further hydrolyze the WAS feed, thus improving the AD step. Sludge cells are lysed and release extracellular and intracellular matter. This matter is now more accessible to the anaerobic micro-organism consortium (Eskicioglu et al. 2007). Solubilization of particulate chemical oxygen demand (pCOD) and reductions of total and volatile solids (TS, VS) are achieved for greater solids reduction rates during mesophilic and thermophilic AD (M/TAD). This typically leads to added pathogen reduction, shorter hydraulic residence times, reduction of residual solids, and smaller reactor volumes. Dewaterability can be positively or negatively affected but increased access to the intracellular matter by the methanogenic bacteria generally improves biogas production by 30-50% (Phothilangka...
Since efficacy of PTs typically increases with an increase in the concentration of feed solids, it is also important to consider cost and energy demands of concentrating the sludge prior to PT (Eskicioglu et al. 2007).

As underlined by most authors studying PT, more research is needed to ascertain the level of benefit that would be gained by applying PTs under full-scale conditions (Bougrier et al. 2005; Benabdallah El-Hadj et al. 2007). A thorough review of PT studies was therefore completed. The works were dissected for reproducibility, cost, energy demands, full-scale applicability, and factor variability (e.g., organic loading rate and retention time). Though numerous variables affect PT and M/TAD performances and few full-scale results were available, the aim of this research was to guide PT design by demonstrating financial and environmental feasibility. A comparative model was created for any conventional WWTP using Microsoft Excel and its Visual Basic Assistant (VBA). The model in conjunction with user defined values (UDVs) creates a treatment and cost output. A preferred process is prescribed based on the assembled results ranges and WWTP operators/designers data inputs (e.g., sludge characteristics and digestion parameters).

The PTs selected for presentation in this paper were ultrasound (ULT), chemical (CM), conventional heating (CH), and microwave heating (MWH), based on energy intensiveness, commonality, feasibility, and novelty, respectively. A handful of review papers based on the quantitative and qualitative benefits of the PTs presented here are already available (Müller, 2001; Pérez-Elvira et al. 2006). The focus of this paper is not to reiterate those reviews but to provide a brief summary of their conclusions (i.e., result ranges, operational settings) as a means of founding the usefulness of this research and to pursue the all-important results outputted from the created model.

### METHODS

A literature dissection of over 100 technical papers was conducted to obtain all significant data on PTs and their combinations. Once comparable data and results were pinpointed (e.g., PS:WAS ratio, pCOD solubilization, biogas increase) a database was created. Values were added from which appropriate observations and trends could be discerned over a variety of studies. Since large results deviations existed within and between studies, a model was required to effectively assess PT suitability to various sludges. It was built to consider raw feed (RF) settings as well as typical biological and other treatment parameters. The model was built to enable or disable Macros in Excel. For those who have enabled Macros, the ‘WWTP Interface’ can be employed. In either case, the data entered is saved to the ‘Backup – Run #’ worksheets. Three runs are initially configured and the output can be based on some or all of them. Runs can be constructed with or without PT. Both cost and energy values are determined from UDV values. Default values were provided as guidelines and recommendations at almost every instance where a user is enabled to enter data. Permutations revolving around fixed plant designs and varied RF settings or PT use were conducted to establish WWTP costs with and without PT. They are referred to herein as base and advanced costs, respectively.

### RESULTS AND DISCUSSION

Specific PT evaluations are presented for literature and subsequent model results. The quantity of UDV values and necessary equations responsible for the creation of the model and its output is too vast to treat in this paper. Essential literature and model variables however, are presented. For all PTs evaluated, the WW feed characteristics for COD, TS, and VS ranged between 13–67, 10–44 and 7–33 g/L, respectively. Their subsequent treatment results for pCOD solubilization, TS and VS reductions were 10–66, 7–36, and 8–67%, respectively. Biogas production improved 5–48%. UDV values for pCOD solubilization, TS, and VS reductions were 40, 20, and 20% respectively. Biogas production was not altered by a UDV but by design using literature biogas production equations (Metcalf & Eddy 2003).

### Ultrasound PT

ULT frequency and specific energy ($E_s$) are the main factors affecting COD solubilization and biogas production. Low frequencies ($<100$ kHz) are thought to promote mechanical and physical degradation while high frequencies promote sonochemical effects and subsequently, matter is further solubilized. Optimal working ranges for frequencies and $E_s$ have been found and do not demonstrate much significant variance regardless of feed characteristics (Bougrier et al. 2005; Benabdallah El-Hadj et al. 2007)). Working ranges are shown in Table 1.

### Chemical PT

Acid and alkaline PTs can be used to degrade complex organic compounds regardless of low temperatures. Alkaline
CM (referred to herein as simply CM) is performed by increasing the sludge pH to 12 and sustaining it for an optimal duration. Complex organics such as polycyclic aromatic hydrocarbons, lipids, and proteins are hydrolysed into smaller and more soluble compounds. CM requires low energy input, solubilizes COD effectively, and provides good sludge dewaterability. Desired bacteria can be harmed however, and chemical addition speeds up equipment corrosion and fouling. Additionally, some of the soluble compounds that are formed are not biodegradable (Méndez et al. 2002; Neyens et al. 2003). Energy demands in CM processes include energy costs of chemical production/procurement, mixing energy, and any heating energy. These can be converted to costs and added to the daily CM usage costs. Working ranges are shown in Table 2.

Conventional heating PT

Temperatures required for conventional heating PT (CH) typically range from 60–180°C. Heating is supplied by either heat exchangers or steam injection. Though CH requires a high increase in energy demand, it is said to be balanced by higher sludge biodegradability and by use of sludge residual heat to maintain the temperature in the digester. Dewaterability and pathogen reduction are increased with thermal pre-treatment and result in reduced sludge disposal costs and improved sludge stabilization. Heat transfer is limited by the wastewater’s (WW) thermal conductivity, density, viscosity, and specific heat. The surface of the material is subjected to heat and heating to the depth of the material is time-consuming (Phothilangka et al. 2006). Energy is also lost in the process. Demands in the CH process include heat and mixing energy. Working ranges are shown in Table 3.

Microwave heating PT

Microwave irradiation has been studied as an alternative to CH. The irradiation corresponds to 1 mm-1 m wavelengths in the electromagnetic spectrum with equivalent frequencies of 300 GHz-300 MHz, respectively. For the heating or drying of thin substances, frequencies of 2,450 MHz with correspondingly short wavelengths (12.24 cm) are adequate. If deep penetration into materials is required, frequencies of 900 MHz with correspondingly long wavelengths (37.24 cm) and energy outputs of up to 100 kW are required. MWH is absorbed selectively by substances containing more moisture, sugars or fats. The distribution of heat in microwave irradiated WW is thus not uniform because the fluid is two-phase (solid and liquid) and heterogeneous in both phases. Warming or cooling the unit as in CH is not required and energy is conserved because microwaves can be instantly activated or deactivated. MWH can be up to 50% more efficient than CH methods. Microwave units also experience less fouling because their surfaces are not brought to the same high temperatures as the surfaces of CH units (Eskicioglu et al. 2007). Energy demands in MWH processes include the necessary conversion efficiencies from “at-the-wall” power to applied heat and mixing energy. Working ranges are shown in Table 4.

WWTP model – comparative evaluation

The cost and energy output is updated simultaneously as the user progresses through the WWTP model. Fundamental equations used include chemical dosage costs (Dc), heating needs (EH), losses (EL), and specific energy (Ee) (Metcalf & Eddy 2003; Benabdallah El-Hadj et al. 2007). They are shown below and were manipulated throughout the model to apply to the chosen design and to present the user with important

### Table 1 | Literature operating ranges for ULT

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Power (W)</th>
<th>Es (kJ/kg TS)</th>
<th>PS Range: WAS Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>20–42</td>
<td>70–300</td>
<td>6,000–18,000</td>
<td>25–33:66–100</td>
</tr>
</tbody>
</table>

### Table 2 | Literature operating ranges for CM

<table>
<thead>
<tr>
<th>Dose (kg/m³ NaOH)</th>
<th>Time (h)</th>
<th>pH</th>
<th>PS Range: WAS Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–21</td>
<td>0.25–24</td>
<td>10–12</td>
<td>0–100:0–100</td>
</tr>
</tbody>
</table>

### Table 3 | Literature operating ranges for CH

<table>
<thead>
<tr>
<th>Temperature (C)</th>
<th>Time (h)</th>
<th>PS Range: WAS Range (Ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50–170</td>
<td>0.25–1</td>
<td>50–100:50–100</td>
</tr>
</tbody>
</table>

### Table 4 | Literature operating ranges for MWH

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Power (W)</th>
<th>Time (h)</th>
<th>PS Range: WAS Range (Ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,450</td>
<td>400–1,250</td>
<td>0.03–0.25</td>
<td>0–50:50–100</td>
</tr>
</tbody>
</table>
results in the same key units (e.g., kWh/d, $/batch). Energy
demands for all PTs selected in this review include (but may
not necessarily require) additional pumping and mixing.
Equations for the two latter variables are well-established in
literature and are thus, not shown here (Metcalf & Eddy 2005).
Variables used in Equation 1 include specific dosage
($/\text{L NaOH or KOH}$) and treatment volume ($V, \text{m}^3$). The
chemical price is market-driven and the number of daily
treatments is determined, in the case of CM, by treatment
time, set-up time, and treatment volume.

$$D_c = D_s \cdot \text{chemical price} \cdot V \cdot \text{of daily treatments} \quad (1)$$

$E_s$ is equivalent to the energy stored divide by the unit mass
(Benabdallah El-Hadj et al. 2007). Though $E_s$ is widely used
to describe energy demands in ULT, it can be adapted to any PT
were an energy variable is known (e.g., $W, \text{kJ}$). Conversion
factors are easily applied to obtain units of $\text{kJ/kg TS}$. Vari-
ables included power ($P, \text{W}$), treatment time ($t, \text{h}$),
treatment volume ($V, \text{m}^3$), and initial solids concentration
($TS_0, \text{kg/m}^3$). Equation 4 demonstrates $E_s$ as the sum of
heating requirements and losses on a basis of mass loading.

$$E_{H} = Q_{i} \cdot \rho \cdot C_p \cdot (T_e - T_i) \quad (2)$$

$$E_L = A \cdot C_p \cdot (T_e - T_{amb}) \quad (3)$$

$$E_s = \left( \frac{(P \cdot t)}{(V \cdot TS_0)} \right) \quad (4)$$

$$E_s = \left( \frac{(E_H + E_L)}{Q_i \cdot TS_0} \right) \quad (5)$$

The flow diagram in Figure 1 was used for the complete
heating needs, losses, and recoveries in the model’s energetic
determinations. The flows and temperatures are noted as $Q$
and $T^*$, respectively, with subscripts referring to origin stream
and/or direction. The dewatering step is labelled DE.

It became clear that most literature data are not fully
comparable. To allow model results to be compared to those
found in literature, a shift was made towards having the
model user define the level of improvements desired with
the use of a specific PT and creating an output showing
associated energy and cost demands. This could be done
because, as mentioned above, working ranges were found
for PT WW feeds, energy, and dosage requirements. Table 5
shows those requirement ranges and the UDVs employed.

RF characteristics are outlined in Table 6. They represent
the UDVs based on the composition of average (UDV$_{avg}$) and
high (UDV$_{high}$) untreated domestic WWs (150). A value of
$1 \times 10^6$ inhabitant equivalents (IE) was used alongside a RF
temperature ($T_{RF}$) of $15^\circ C$ and mesophilic digestion
temperature of $35^\circ C$.

PT potential was evaluated with regards to energy con-
sumption and yearly cost. An assessment of base and
advanced costs was produced for average and high flows
for each PT. In all cases treatment time energy price methane
heating and electrical values of 0.25 h, 0.04 $/\text{kWh}
21,600 $/\text{m}^3$, and 12,600 $/\text{m}^3$, respectively, were used.

Figure 2 provides the costs and impacts for each PT on
affected WWTP units. Additional pumping and mixing ener-
gies and costs were not shown as they represent less than 1% of
total PT operation demands. Daily revenues gained refers
to both costs saved and added profit.

It is evident that PT use demands additional operating
funds. Those funds can be recuperated as heat recovered
($E_q$), biogas improvements, and reductions to demands at the
M/TAD, DE, and SD steps. Biogas, sludge disposal (SD) and
DE gains for UDV$_{avg}$ and UDV$_{high}$ conditions were $889, 443,$
and $27 $/d Gained as well as $2658, 973,$ and $82 $/d Gained,
respectively. These results were not affected by PT selection,
regardless of RF characteristics, because gains were depen-
dent on UDVs for pCOD solubilization, TS, and VS reduc-
tions. Since ULT and CM were assumed to have the same

### Table 5 | Advanced hydrolysis requirements and selections for each PT

<table>
<thead>
<tr>
<th>UVT</th>
<th>CM: D$_s$</th>
<th>CH: T</th>
<th>MWH: E$_s$</th>
<th>PS: WAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kJ/kg TS)</td>
<td>(k/m$^3$, NaOH)</td>
<td>($)</td>
<td>(kJ/kg TS)</td>
<td>(Ratio)</td>
</tr>
<tr>
<td>UDV 10,000</td>
<td>4</td>
<td>120</td>
<td>8,000</td>
<td>0.100</td>
</tr>
</tbody>
</table>

### Table 6 | User-specified RF characteristics

<table>
<thead>
<tr>
<th>UDV</th>
<th>$Q_{ref}$</th>
<th>COD$_{ref}$</th>
<th>TS$_{ref}$</th>
<th>VS$_{ref}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg</td>
<td>0.46</td>
<td>0.43</td>
<td>0.72</td>
<td>0.36</td>
</tr>
<tr>
<td>high</td>
<td>0.75</td>
<td>0.80</td>
<td>1.20</td>
<td>0.66</td>
</tr>
</tbody>
</table>
negligible impact on WAS temperature, $E_R$ is comparatively minute. Costs increase with higher solids loadings. Though CH demands more heat input than MWH, based on UDV for PT temperature settings, more heat is recovered and overall costs are not significantly greater than MWH. Final cost results for the WWTP model are shown in Table 7.

It is clear that PTs requiring high energy inputs, to achieve desired hydrolysis levels that produce comparable biogas improvements, are more costly. Total advanced costs incorporate PT use and are higher for both ULT and CM. Larger deviations between PTs are again observed when solids loadings are increased. Daily gains for base and advanced results are independent of selected PT and current model settings. They were found to be 4,173 and 5,062 $/d$ as well as 12,619 and 15,257 $/d$ for UDV$_{avg}$ and UDV$_{high}$ conditions, respectively.

It is important to note that these costs and gains do not take into consideration design modifications that must occur when larger flows are experienced. Base and advanced costs treat 100% of the WAS stream. The user is capable of adapting treatment to more complex conditions.

To provide a clearer understanding of the incorporated capabilities of the model, Figure 3 was added. It demonstrates the single sheet output and holds all of the significant results for any run the user decides to showcase. A more in-depth output is created alongside and consists of over 10 pages of tabulated and pre-designed figures to compare any and all of the runs.

### CONCLUSIONS

Vast quantities of literature data were collected to establish working ranges for sludge hydrolysis levels and subsequent digestion improvements. These data were established and incorporated into the evaluation of a conventional WWTP model in Microsoft Excel. For the context of this paper many values and methods were necessarily omitted. The variables presented however, were sufficient to establish an understanding of the operational cost trends for ULT, CM, CH,
and MWH. Base and advanced costs were obtained for all four PTs. These costs depend on UDVs and the optimal PT based on costs alone was MWH.

The nature of this work and the capabilities of this model are leading to definite answers on PT suitability in a full-scale design. Permutations are easily handled and various low, average, and high UDVs will affect a user’s output. When only solids loadings are increased it was found that, on average, costs were affected (upward) by 0.0086 $/m^3 Q_{RF}.

A model is now available to financially assess the highly-touted benefits of PT technologies.

Although overall operating costs increased for all PTs considered here (and these increases were exclusive of capital costs), there may be other environmental benefits (e.g., pathogen reduction, lowered use of chemical agents) that will make PT desirable. For instance, at longer sludge transport distances than the roundtrip UDV of 30 km, a cost breakeven point would be reached.

REFERENCES


