Effect of ambient temperatures on disinfection efficiency of various sludge treatment technologies
Katrin Bauerfeld

ABSTRACT

Sewage sludge produced during municipal wastewater treatment has to be treated efficiently in order to reduce impacts on the environment and on public health. In Germany and many countries, large quantities of sludge are reused in agriculture in order to recycle nutrients and organic material. In order to quantify the effect of different ambient temperatures on conventional and advanced sludge treatment technologies as well as on disinfection efficiency, a comprehensive research study was performed at Braunschweig Institute of Technology. The detailed results show that ambient temperature has a strong effect on biological liquid sludge stabilization and on natural dewatering and drying technologies, although microbiological quality of treated sludge, indicated by Escherichia coli concentration, does not meet the requirements for unrestricted reuse in agriculture. Composting and lime treatment of sludge are most efficient on reducing E. coli, as high temperatures and high pH values arise in the material respectively.

Key words | agricultural reuse, disinfection, phyto-toxicity, sludge stabilization

INTRODUCTION

Each year, around two million tons dried solids of sewage sludge are produced in German municipal wastewater treatment plants. Nearly one third is directly reused as organic fertilizer in agriculture, following the legal requirements given by the EU Sewage Sludge Directive (86/278/EEC 1986) and the German Sewage Sludge Ordinance (AbfKlaerV 1992). Both encourage and control sludge application to agricultural land, although the quality standards for heavy metals and organic pollutants set in the national Sludge Ordinance are a lot stricter than EU legislation. Nevertheless, since 2002, several approaches have been followed to tighten these national quality standards for sludge and biosolids, but until now, none of the suggestions have been adopted. Recent discussions do not only include the amendment of limit values for organic and inorganic sludge constituents, but also limits on the concentration of selected microorganisms like Escherichia coli or Salmonella which indicate a fecal origin.

As the reduction or inhibition of biological degradation processes, in order to ensure a safe reuse or disposal of the material, is the basic aim of all sludge treatment processes, the reduction of pathogens has long played a minor role when discussing legal requirements and designing sludge treatment processes in Germany. In addition, high hygienic and health standards as well as strict regulations on controlling vectors when applying secondary raw materials in agriculture are responsible for sludge disinfection having not been an urgent issue so far. However, due to a growing number of epizootic diseases as well as to recent water and food safety scandals like the outbreak of enterohemorrhagic E. coli in 2011, suspicions have been raised that organic fertilizer could be the source of the problem. Therefore the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety currently works on an amendment of the Sewage Sludge Ordinance including stricter limit values for pollutants and treatment standards for pathogen control (BMU 2010).

Against this background, different sewage sludge treatment technologies commonly used in Germany and Central Europe have been evaluated in small-scale tests at TU Braunschweig regarding stabilization procedure, pathogen reduction and phyto-hygienic safety of sludge products. The selection of treatment technologies included aerobic and anaerobic liquid sludge stabilization, sludge composting with wood chips, slake and quick lime treatment as well as natural dewatering and drying technologies. Although all

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these treatment options have already been described extensively in international literature with varying emphases since the 1970s, this study focuses on a comparison of stabilization and disinfection efficiency. In contrast to other studies on single treatment technologies, sludge origin, composition and operating conditions could be unified for all single tests in order to focus on temperature dependency of the different processes and the quality of the treated sludge. Therefore the results of this study allow a comprehensive interpretation.

This report gives a summary of the most important aspects on this research topic based on Bauerfeld (2012).

**METHODS**

For all smale-scale tests on biological and alkaline treatment, raw sludge from municipal wastewater treatment plants was used in three different mixing ratios of primary sludge (PS) and secondary sludge (SS) in order to represent different sludge qualities. The sludge mixing ratios according to dry matter content were SS:PS = 1:1, 3:2 and 2:1. Table 1 shows the biochemical characteristics of the sludge mixtures used in this study.

All tests on biological and alkaline treatment were set up in temperature and moisture controlled chambers simulating ambient temperatures of 5 to 30°C at an adjusted humidity of 60 ± 5%. In addition to these conditions, aerobic and anaerobic liquid sludge treatment tests were set up at 55°C, providing thermophilic temperatures as reference on disinfection efficiency. All biological and alkaline treatment tests were operated as single tests for each sludge mixture.

In addition to biological and alkaline treatment, natural dewatering technologies for aerobically pretreated raw sludge (incomplete stabilization) were tested outdoors, in order to quantify the efficiency of low-tech dewatering solutions. In this case, conventional drying beds as well as reed beds and solar sludge drying were chosen. Again, all tests were operated as single tests.

Table 2 lists details about the experimental set-up including sizing and equipment components.

The monitoring program for the treatment processes followed the suggestions of the German Water Association (ATV/VKS 1988) and the World Health Organization (WHO 2006) including water, solids and nutrient balances as well as the determination of levels of E. coli as pathogenic indicator bacteria. Phytotoxicity was tested using garden cress (Lepidium sativum) following suggestions on compost quality control (BGK 1998). Table 3 lists the German and European standard methods chosen for characterization of the sludges.

The experimental results in combination with literature data were used to define criteria that mark completely stabilized high-quality sludge after biological treatment at different temperatures:

- high organic matter reduction ≥40% for aerobic and anaerobic liquid sludge treatment, ≥50% for composting in reference to full-scale experiences;
- low biochemical oxygen demand/chemical oxygen demand (BOD/COD)-ratio ≤0.15 in liquid sludges in reference to full-scale experiences and according to the literature (e.g. Tchobanoglous et al. 2003; von Sperling & Goncalves 2007);
- low concentrations of organic acids in digested sludge liquid ≤200 mg HAc/l in reference to full-scale experiences;
- a residual gas yield of treated sludge for mesophilic post-digestion RGY35 c ≤ 100 l/kg VS0 according to laboratory-scale and full-scale experiences in combination with low concentrations of organic acids.

The dependency of ambient temperature on organic matter degradation for aerobic and anaerobic degradation could be quantified using the Arrhenius relation following first-order kinetics in regard to Motulsky & Christopoulos (2004):

\[ k_{T2} = k_{T1} \cdot e^{(T2-T1)} \]

where:
- \( k_{T2} \) is the kinetic constant at temperature \( T2 \)
- \( k_{T1} \) is the kinetic constant at temperature \( T1 \)
- \( T \) is the temperature in °C

This report gives a summary of the most important aspects on this research topic based on Bauerfeld (2012).

**Table 1 | Biochemical characteristics of the raw sludges (mixtures of PS and SS in different ratios)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Liquid sludge</th>
<th>Dewatered sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH value</td>
<td>[-]</td>
<td>6.3–7.6</td>
<td>6.5–7.2</td>
</tr>
<tr>
<td>Total solids (TS)</td>
<td>[kg/m³]</td>
<td>11.1–29.5</td>
<td>140–165</td>
</tr>
<tr>
<td>Volatile solids (VS)</td>
<td>[%]</td>
<td>68.6–78.9</td>
<td>69.0–74.9</td>
</tr>
<tr>
<td>COD</td>
<td>[mg/l]</td>
<td>12,010–46,810</td>
<td>164,050–246,950</td>
</tr>
<tr>
<td>BOD₅</td>
<td>[mg/l]</td>
<td>6,546–19,840</td>
<td>Not analyzed</td>
</tr>
<tr>
<td>NH₄-N</td>
<td>[mg/l]</td>
<td>21.2–155</td>
<td>393–585</td>
</tr>
<tr>
<td>KN</td>
<td>[mg/l]</td>
<td>508–1,764</td>
<td>6,120–9,360</td>
</tr>
<tr>
<td>PO₄-P</td>
<td>[mg/l]</td>
<td>7.8–33.6</td>
<td>42.1–119</td>
</tr>
<tr>
<td>Pₜot</td>
<td>[mg/l]</td>
<td>186–610</td>
<td>2,410–4,189</td>
</tr>
<tr>
<td>E. coli</td>
<td>[MPN/g TS]</td>
<td>15.9–48.4 × 10⁶</td>
<td>33.8–75.3 × 10⁶</td>
</tr>
</tbody>
</table>
Effect of ambient temperatures on disinfection for sludge treatment technologies

K. Bauerfeld

Effect of ambient temperatures on disinfection for sludge treatment technologies

Table 2 | Experimental set-up of research programme on sludge stabilization and disinfection at different ambient conditions

<table>
<thead>
<tr>
<th>Sludge treatment technology/temperature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerobic and anaerobic post-stabilization/5–30 °C</td>
<td>Batch reactors, liquid sludge volume ≤23 l; continuous aeration for aerobic conditions (O2-saturated); anaerobic digestion with daily gas quantity measurement; weekly sludge sampling and gas quality measurement</td>
</tr>
<tr>
<td>Composting with wood chips/5–30 °C</td>
<td>14 days pretreatment in aerated static piles (closed systems, aeration intensity = 300 l/h), total volume = 100 l dewatered sludge + woodchips (sludge:woodchips mixing ratio = 30:70 Vol%), moisture adjustment to TS0 = 60%, continuous emission and temperature control; followed by open window composting up to 9 weeks with weekly turning and moisture control; weekly sampling of compost</td>
</tr>
<tr>
<td>Slaked lime treatment/5–30 °C</td>
<td>Batch test, 30 l liquid sludge + Ca(OH)2, lime application according to sufficient pH-increase ≥12.5, followed by 3 months' storage; weekly sludge sampling</td>
</tr>
<tr>
<td>Quick lime treatment/5–30 °C</td>
<td>Batch test, 30 l dewatered sludge sludge + CaO, lime application according to sufficient pH-increase ≥12.5 and temperature rise ≥55 °C for two hours, followed by 3 months' storage; weekly sludge sampling</td>
</tr>
<tr>
<td>Conventional drying bed and reed bed drying/4–24 °C (June–September)</td>
<td>Outdoors, semi-continuous liquid sludge application of 15 and 25 kg TS/m² on sand and gravel drainage layers (10 cm gravel, sized 8–16 mm, topped with 15 cm sand, sized 0–8 mm) during 16 weeks; reed bed tests with Phragmites australis (same drainage layer set-up and sludge application as conventional drying tests, reed density: 19 plants/m²); total area 0.3–0.5 m²/test; weekly sludge sampling</td>
</tr>
<tr>
<td>Solar sludge drying/−2–22 °C (January–May)</td>
<td>Outdoor batch tests with 12 cm dewatered sludge layer in small-scale greenhouses (0.3–0.5 m²) for 15 weeks), controlled ventilation and 2–3 complete turnings/week; weekly sludge sampling</td>
</tr>
</tbody>
</table>

Table 3 | Standard methods for characterization of the raw sludges

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total solids/organic solids</td>
<td>DIN EN 12880, 2001–02/DIN EN 12879, 2001–02</td>
</tr>
<tr>
<td>COD</td>
<td>DIN 38409 H41, 1980–1</td>
</tr>
<tr>
<td>BOD5</td>
<td>DIN 38499 E, 1998–05</td>
</tr>
<tr>
<td>NH4-N/KN</td>
<td>DIN 38406-5, 1983–10/American Standard Methods 12/1965</td>
</tr>
<tr>
<td>PO4-P/P tot</td>
<td>DIN 38405 D11, 1983–4</td>
</tr>
<tr>
<td>Gas quality (CO2, CH4)</td>
<td>Gas chromatography FID</td>
</tr>
<tr>
<td>Organic acids</td>
<td>Gas chromatography FID</td>
</tr>
<tr>
<td>Phyto-toxicity</td>
<td>Garden cress test; BGK (1998)</td>
</tr>
<tr>
<td>E. coli</td>
<td>DIN 10164-1, 1986–08, ASU 06.00-24</td>
</tr>
</tbody>
</table>

with $k_{T1,T2} =$ reaction constant at reference temperature $T1 \text{ [°C]}$ and examined temperature $T2 \text{ [°C]}$; $\theta =$ temperature activity coefficient [–].

For alkaline treatments, the treatment criteria were defined after the recommendations of ATV/VKS (1988), Tchobanoglous et al. (2003) and Bitton (2005):

- pH-value 12.5 ± 0.3 during 3 months' storage for slaked and quick lime treatment;

- temperature rise ≥55 °C for two hours for quick lime treatment.

The treatment criteria for natural dewatering and drying technologies were chosen from full-scale operation experiences:

- liquid sludge dewatering in conventional drying beds and reed beds from initial solids content ($T_{S0}$) ≤ 50 kg/m³ to a solids content in the treated sludge ($T_{S\text{end}}$) ≥ 300 kg/m³;

- dewatered sludge drying in solar sludge drying tests from $T_{S0}$ ≤ 200 to $T_{S\text{end}}$ ≥ 700 kg/m³.

Following these criteria, the duration of the processes could be defined and end-product quality could be specified.

RESULTS AND DISCUSSION

Effect of sludge quality on biological sludge stabilization

Technical systems for sludge treatment, especially those using biological degradation, are basically influenced by sludge composition and treatment temperature. Other climatic influences are negligible. In order to evaluate basic temperature indicated relations between sludge degradation and stabilization/disinfection, the effect of sludge

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composition on degradation progress has to be considered: Preferably, the effect on degradation is kept low while at the same time reflecting full-scale reality in sludge quality variation.

Since the 1970s, full-scale experiences and research reports published in Germany show a lot of experiences on sludge composition and its influence on degradation results (e.g. Eickhoff 1969; Kapp 1984; Roediger et al. 1990). These results are basically also described for sludge treatment considering other boundary conditions, especially in warm climates (Ludovice 2006). In general, initial organic matter concentration could be specified as the main factor influencing degradation time for aerobic processes, showing a quasi-linear relation in these studies. Gas quantity and gas composition resulting from anaerobic processes depend on the percentage of PS in raw sludge: the higher the PS share, the higher the gas amount, but the lower the methane content.

In the present study, three sludge qualities, reflecting different mixtures of PS and SS with different biochemical characteristics have been used for stabilization tests (see Table 1). Within these variations of initial sludge composition, the following general conclusions from the aerobic and anaerobic batch tests could be drawn:

- For the different sludge qualities used in this study, no relation between sludge composition and aerobic as well as anaerobic degradation could be measured, if the stabilization criteria shown above were considered. Here, the range of variation of sludge characteristics was lower than the range of variation stated in other research reports that clearly indicated an effect on degradation processes.
- For anaerobic processes, sludge composition only affected gas amount. Degrading ability of the organic matter as well as gas composition was not influenced.

Therefore, the following results on temperature-stabilization/disinfection relations can be considered as basic relations within the limits of sludge quality variation realized in this study.

**Effect of ambient temperature on sludge stabilization**

The experimental results on biological sludge treatment showed that aerobic post-stabilization is suitable for both cold and warm climates, taking into account longer sludge retention times at decreasing temperatures considering the stabilization criteria given above. However, for a fully completed anaerobic digestion (considering residual gas yield (RGY)), temperatures above 25 °C were necessary. Figure 1 shows the treatment duration evaluated for aerobic and anaerobic post-stabilization depending on temperature in comparison to literature data variations. The variations in treatment duration of other studies can be related to different sludge origins and different criteria for defining complete stabilization. Approximating the data of this study, the recommended treatment duration \( t_{\text{aerobic}} \) and \( t_{\text{anaerobic}} \) depending on temperature \( T \) [°C] can be calculated as follows:

\[
\begin{align*}
t_{\text{aerobic}} &= 43.9 \cdot e^{-0.055T} + 5.43 \\
t_{\text{anaerobic}} &= 329 \cdot e^{-0.082T} + 4.17
\end{align*}
\]

As indicated by Figure 1, the anaerobic degradation process showed a higher temperature dependency than the aerobic degradation process. The Arrhenius relation gives the following expression in regard to VS reduction:

\[
\begin{align*}
\text{Aerobic post-stabilization: } k_{\text{VS}}(T) &= k_{\text{VS,30}} \cdot 1.043^{(T-30)} \\
\text{Anaerobic digestion: } k_{\text{VS}}(T) &= k_{\text{VS,30}} \cdot 1.085^{(T-30)}
\end{align*}
\]

In contrast to aerobic and anaerobic liquid sludge treatment, composting of dewatered sewage sludge with organic bulking material was predominantly affected by ambient temperature variations during the initial heating phase. During the 14 day pretreatment phase in aerated static piles, 30% of organic matter was reduced at mesophilic ambient temperature conditions, nearly 20% at psychrophilic temperatures. Accordingly, open windrow post-treatment duration and thus degradation time in total, increases with decreasing temperature. The total treatment duration \( t_{\text{composting}} \) including the 14 day pretreatment can be calculated as follows depending on ambient temperature \( T \) [°C]:

\[
t_{\text{composting}} = 45.9 \cdot e^{-0.055T} + 18.3
\]

The temperature dependency of VS reduction considering the Arrhenius relation can be specified as:

\[
\text{Two-stage composting: } k_{\text{VS}}(T) = k_{\text{VS,30}} \cdot 1.019^{(T-30)}
\]

Hence, the temperature dependency of a two-stage sludge composting process with wood chips was weaker than for aerobic liquid sludge stabilization. Instead, degradation and disinfection were mainly influenced by process
control (e.g. bulking material characteristics, oxygen supply, water content, turning).

Next to biological treatment options, alkaline treatment is one of the most common sludge treatment technologies, especially for small-scale wastewater treatment plants. The experiments on this treatment technologies confirmed that the addition of quick lime and slaked lime in order to inhibit biological reactions in sludges basically depended on sludge physico-chemical characteristics like solids content and buffering capacity. Ambient temperature only influenced water removal during storage of the material. For realizing long-term pH-values above 12.5, the required quick lime quantity amounted to 15 to 45% of sludge dry mass. A temperature rise above 55°C required higher quick lime quantities multiplied by 1.5 to 2.5 in comparison to sufficient pH increase only. Typical slaked lime application rates for liquid sludge treatment varied within 5 to 8 kg Ca(OH)₂/m³ for sufficient pH increase. All determined lime quantities were within the range of results published by Eriksen et al. (1996) and Ødegaard et al. (2002) which are quoted in numerous publications on alkaline sludge treatment.

Water removal in natural dewatering and drying systems strongly depends on climatic conditions. According to the water losses by evaporation, drainage and in case of reed bed systems also plant uptake, annual sludge solids loading rates as most important design data can be calculated for different climatic conditions. Due to the semi-continuous tests in this study, in temperate climates, a mean annual sludge solids loading rate (BTS) of 15 to 55 kg/(m² a) can be realized for liquid sludge dewatering up to TS_end ≥ 300 kg/m³ in conventional drying beds and reed bed systems. Compared to cold climates, this means a nearly doubled sludge loading rate for the same dewatering result. Nevertheless the sludge load for reed bed treatment was limited to an annual nitrogen load of below 0.5 kg/(m² a) and a nitrogen concentration below 50–200 mg/l according to Jordan (2005) in order to keep a healthy Phragmites stock. Most effective natural drying system was solar sludge drying, usually operated with
dewatered sludge intending to reach a total solids content of \( TS \geq 700 \text{ kg/m}^3 \). Table 4 shows all design parameters derived from the study results considering the treatment objectives shown above.

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<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Drying bed</th>
<th>Reed bed</th>
<th>Solar drying</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cold climate:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean annual temp.</td>
<td>-2°C</td>
<td></td>
<td>8,400 J/(cm² a)</td>
</tr>
<tr>
<td>( B_{TS} )</td>
<td>15–30</td>
<td>not</td>
<td>70–80</td>
</tr>
<tr>
<td>Water loss</td>
<td>0.25–0.5</td>
<td></td>
<td>0.25–0.3</td>
</tr>
<tr>
<td><strong>Temperate climate:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean annual temp.</td>
<td>+8°C</td>
<td></td>
<td>12,300 J/(cm² a)</td>
</tr>
<tr>
<td>( B_{TS} )</td>
<td>25–55</td>
<td>40–80</td>
<td>130–150</td>
</tr>
<tr>
<td>Water loss</td>
<td>0.4–0.9</td>
<td>0.7–1.4</td>
<td>0.45–0.55</td>
</tr>
<tr>
<td><strong>Tropical climate:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean annual temp.</td>
<td>+25°C</td>
<td></td>
<td>17,500 J/(cm² a)</td>
</tr>
<tr>
<td>( B_{TS} )</td>
<td>50–100</td>
<td>60–160 (-220)</td>
<td>230–300</td>
</tr>
<tr>
<td>Water loss</td>
<td>0.8–1.6</td>
<td>1.3–2.7 (-3.6)</td>
<td>0.8–1.1</td>
</tr>
</tbody>
</table>

Effect of ambient temperature on sludge disinfection

Figure 2 shows the results of \( E. coli \) determination in raw liquid sludge for aerobic and anaerobic stabilization and for aerobically pretreated raw sludge (no complete stabilization according to criterion \( RGY_{55} C \leq 100 \text{ l/kg VS}_0 \)) before natural dewatering as well as in the treated material at all temperatures. The columns mark the range of data (each sludge analyzed in triplicates) for the single tests on different sludge treatment technologies. The maximum reduction rate for each treatment option is quoted.

Furthermore the results on \( E. coli \) concentrations showed that unlike stabilization time for biological treatment processes (see Figure 1), a significant effect of ambient temperature on disinfection efficiency could only be observed during anaerobic digestion. The higher the digestion temperature, the higher the \( E. coli \) reduction. Nevertheless, maximum \( E. coli \) reduction was below two orders of magnitude, being within the same range as for reed bed dewatering of aerobically pretreated sludge. Dewatering in conventional drying beds did not give clear results, as in some tests an \( E. coli \) growth could be determined. Quick lime treatment was the only method to significantly reduce \( E. coli \) in liquid sludge below levels for safe reuse of the material according to WHO and EU suggestions (WHO 2006 and DG Environment 2000).

The results of the \( E. coli \) determination before and after treatment of dewatered sludge are shown in Figure 3.
According to the concentrations measured in dewatered raw sludge and in sludge after composting, quick lime treatment and natural drying, composting and lime treatment are both suitable to achieve good disinfection results. In these tests, the limits suggested by WHO and according to EU regulations could be met. Of all treatment processes for dewatered sludge, composting was the only method with slight effects of ambient temperature on disinfection results with higher reductions the higher the ambient temperature and thus core temperature in the compost material. Here, a temperature rise up to 63°C for several days could sufficiently reduce *E. coli*.

**Phyto-toxicity of treated sludges**

All sludges treated at different ambient temperatures were tested on phyto-toxicity by cress tests in addition to *E. coli* concentration. Figures 4 and 5 show the results of the phyto-toxicity tests for the treated liquid and dewatered sludges. The results are plotted as relative change of cress yield in sludge–soil mixtures (different ratios) according to BGK (1998). Again, the columns mark the range of data (measured as triplicates for each sludge) analyzed in the different single tests on each treatment technology. The results show that all treated liquid and dewatered sludges reach the minimum yield required for being non-phytotoxic. An increase in plant yield could be observed for digested and composted sludge. This plant growth can be interpreted as a result of the fertilizing effect of the treated sludge, defining these sludges as most appropriate for agricultural reuse. Nevertheless the cress test does not qualify for any quantitative relations between an increase in cress yield and the nutrient content in the sludge products (e.g. nitrogen and phosphorus).

**CONCLUSIONS**

This research on the relation between ambient temperatures and stabilization duration and disinfection efficiency highlights some important aspects when choosing the most appropriate sludge treatment technology for different conditions. Although it must be clear that the results shown above still have to be evaluated in large scale and that for adequate sludge management additional local factors besides climatic have to be considered, the following important conclusions can be drawn.

As anaerobic digestion is recommendable at temperatures above 25°C in order to produce a completely stabilized sludge, this process does not necessarily need additional heating to common mesophilic operational temperatures of 35–37°C in warm climate regions, especially as an adequate hygienic quality due to *E. coli* concentrations can apparently be met at thermophilic conditions only. Therefore, if disinfection does not play any important role regarding sludge disposal, energetic benefits
due to biogas production and the reduction of technical equipment and energy demand in simple digesters may shift common results of cost–benefit analyses for anaerobic in comparison to aerobic liquid sludge treatment processes, despite higher treatment duration and thus higher digester volumes. Nevertheless, composting of sewage sludge showed the highest advantages for a safe reuse of the material in agriculture with lower dependency on ambient...
temperatures as biological liquid sludge degradation. High \( E.\ coli \) reduction and good results of phyto-toxicity tests imply not only hygienic safety of the product but also an improvement of crop yield. Therefore the reuse of composted sludge does not only provide an alternative for safe disposal but may also provide advantages for agriculture, e.g. the compensation of mineral fertilizers. Nevertheless, a pre-dewatering of liquid sewage sludge is necessary and nutrients as well as pollutant concentrations should also be considered.

Similar to composting, alkaline treatment produces good disinfection results, especially when adding quick lime and thus rising temperature in the sludge mixture. But as degradation processes are just inhibited and the addition of lime to sludge solids results in higher sludge masses/volumes for transportation and disposal, the benefits must be carefully evaluated. Nonetheless, the process does not depend on climatic conditions and can therefore be easily realized whenever possible due to final disposal options. One of the main advantages of alkaline treatment is the relatively low demand of operational know-how and manpower in comparison to biological treatment options. This aspect qualifies alkaline treatment especially for small wastewater treatment plants worldwide.

Natural dewatering and drying of pretreated sludge as low-tech possibilities for reducing sludge volume strongly depend on climatic conditions and are therefore advantageous at warm climatic regions, especially if land space required does not play any important role. Nevertheless, these treatment options do not provide any significant degradation of the solids and thus no further stabilization. In addition to relatively low effects on \( E.\ coli \) reduction, these processes can therefore only be recommended for agricultural reuse of the treated sludge when combining with composting, for example.

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