Faecal coliform die-off in wastewater storage and treatment reservoirs


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Abstract This paper describes faecal coliform (FC) removal in pilot-scale Wastewater Storage and Treatment Reservoirs (WSTR) in northeast Brazil. FC decay during the filling phase of WSTR was very reduced, suggesting that these reactors should be filled as quickly as possible, and subjected to the highest organic loading that will not cause odour emissions. The highest loading employed in this study was 659 kg BOD$_5$/ha.d, causing no nuisance conditions. During the resting phase, FC decay rate decreased exponentially and Chick’s law was modified. The time into the resting phase for FC to reach $10^3$ cfu/100 mL ranged from 15 to 25 days as WSTR depth varied from 2.00 to 6.50 m. The performance of sequential batch-fed waste stabilization ponds (SBFWSP) in removing FC was compared to that of waste stabilization ponds (WSP) operated in series. In general, SBFWSP were cheaper than WSP in series. When provision of volume to store the winter effluents is considered, a WSP system presents a higher benefit/cost ratio than a hybrid WSP-WSTR system, but the adoption of the latter can double the annual net return for a rainy season of 5 months for instance.

Keywords Wastewater; storage; faecal coliforms; unrestricted irrigation; financial analysis

Introduction
Unreliable rainfall (300–1000 mm/year, distributed over 3–5 months) limits agricultural production in most of the northeast region of Brazil. Wastewater reuse is a common practice all over the world and constitutes a large part of the water resources directed to irrigation in arid regions (Arar, 1991). The World Health Organisation has considered waste stabilization ponds (WSP) as one of the most appropriate technologies for the treatment and subsequent reuse of wastewater for agricultural irrigation. The treated wastewater must have no more than $10^3$ faecal coliforms (FC) per 100 mL and no more than 1 intestinal nematode egg per litre for unrestricted irrigation (WHO, 1989). During the wet season the effluents of WSP systems, unless they are stored for use during the irrigation season, are literally wasted. In the early 1970s Israeli authorities started storing these winter effluents in large reservoirs. They noticed that these reservoirs not only stored the wastewater but also conferred on it a certain degree of treatment (Juanico and Shelef, 1991). Nowadays this technology is known as Wastewater Storage and Treatment Reservoirs – WSTR (Mara et al., 1996). This paper describes FC removal in a pilot-scale WSTR station in northeast Brazil.

Materials and methods
The research was conducted on pilot-scale WSTR at EXTRABES – Estação Experimental de Tratamentos Biológicos de Esgotos Sanitários (Experimental Centre for Biological Treatment of Domestic Sewage), which forms part of the Universidade Federal da Paraíba, in Campina Grande, Paraíba, Northeast Brazil (7°13’11’S; 35°52’31”W, 550m amsl). The pilot-scale station comprised four reservoirs and one anaerobic pond, used to feed the reservoirs in some experiments (Table 1). Nine experiments, each with different operational features, were performed on the WSTR. The experiments were gathered in two groups: A and
C. A number was added to the experiments in an increasing order of filling time in each group (Table 2).

Experiments performed on WSTR1 and WSTR2 (identical reservoirs) had the anaerobic pond effluent (APE) as the influent wastewater (Group A). Experiments done on WSTR4 and WSTR5 (Group C) had raw municipal sewage (RMS) as the influent sewage and were performed in pairs, one on WSTR4 and the other on WSTR5, with the only difference between them being that WSTR5 was covered by ferrocement tiles. The anaerobic pond was operated with an MRT of 1 day during EA3 (chronologically, the first experiment) and 0.5 day during the others.

Samples from several levels (II in Group A and 3–7 in Group C) in the reservoirs were collected weekly at 0800 h, following the recommendations of APHA (1992). Samples for DO, temperature and pH were collected at 1500 h as well (not done in EA1, nor in Group C). During the reservoirs filling phases, the APE and/or the RMS were also sampled at 0800 h.

FC enumeration was done by the membrane filter technique using Oxoid membrane lauryl sulphate broth with incubation at 44.5 °C for 24 h (Ayres & Mara, 1996). BOD5 was determined according to the standard BOD bottle procedure (APHA, 1992). Chl a was determined using the methanol extraction technique described by Jones (1979). Temperature was measured with a mercury-filled thermometer immediately after sample collection. pH was measured electrometrically by a Jenway 3030 pH meter with a Russel BNC electrode and a Jenway PCT 121 temperature compensation probe. DO was determined electrometrically with an oxygen-sensitive membrane probe (YSI model 5720A) connected to a YSI model 54A DO meter.

**Results**

Most of the surface organic loadings applied to the WSTR (117–659 kg BOD5/ha.d) were higher than the recommended value of 150 kg BOD5/ha.d for the safe operation of WSTR in Israel (Juanico and Shelef, 1994). However, due to the much higher temperature of Northeast Brazil in comparison to Israel, offensive odour emissions were not noticed.

FC numbers during the filling phases of the WSTR were in the range $10^6$ – $10^8$ per 100 mL, generally following the strength of their influent (either APE or RMS), although they were slightly lower than in the influent wastewater. FC numbers tended to remain at their initial level or decrease only slightly, especially in the longer experiments, until the end of the filling phase; thus there is no advantage of having a prolonged filling time in WSTR. Reservoirs should be filled as quickly as possible, subjected to the highest organic loading.

### Table 1 Physical features of the pilot-scale station at EXTRABES

<table>
<thead>
<tr>
<th>WSTR1/ WSTR2</th>
<th>Internal diameter (m)</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Mean depth (m)</th>
<th>Superficial area (m²)</th>
<th>Net volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSTR3/ WSTR5</td>
<td>-</td>
<td>3.00</td>
<td>1.87</td>
<td>3.40 ± 2.00</td>
<td>5.61</td>
<td>19.07 ± 11.22</td>
</tr>
<tr>
<td>Anaerobic pond</td>
<td>-</td>
<td>6.00</td>
<td>2.20</td>
<td>3.50</td>
<td>7.20</td>
<td>46.20</td>
</tr>
</tbody>
</table>

*experiment I; b experiment II.

### Table 2 Operation of the pilot-scale WSTR station

<table>
<thead>
<tr>
<th>Experiments</th>
<th>EA1</th>
<th>EA2</th>
<th>EA3</th>
<th>EA4</th>
<th>EA5</th>
<th>EC1</th>
<th>EC2</th>
<th>EC3</th>
<th>EC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling time (days)</td>
<td>15</td>
<td>18</td>
<td>35</td>
<td>35</td>
<td>41</td>
<td>23</td>
<td>23</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Resting time (days)</td>
<td>105</td>
<td>52</td>
<td>124</td>
<td>54</td>
<td>91</td>
<td>75</td>
<td>75</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>

*Covered WSTR.
that will not cause odour emissions (659 kg BOD₅/ha.d or more). After the end of the filling phase (beginning of the resting phase) an accentuated fall in FC numbers started, which lasted until FC numbers reached 10 cfu/100 mL. Chl a increased from the beginning of the filling phase until around the end of this phase, after which its concentration decreased towards the end of experiment. WSTR 4, which was shallower than WSTR 1 and WSTR 2, had the highest Chl a concentrations found in this study, around 1200 µg/L.

Temperatures in the 0800 h samples ranged from 24 to 28 ºC, while in the 1500 h samples it varied from 24 to 30 ºC. pH presented the general trend of slightly increasing over time. However, the pH value of 9.0, above which FC decay is accelerated (Pearson et al., 1987), was not reached. The WSTR were anaerobic (DO concentration < 1 mg/L) most of the time, but with higher concentrations in the upper levels, towards the end of experiments and in the 1500 h samples.

Discussion

The FC decay rate during the resting phase of all experiments was computed for each consecutive pair of FC numbers (geometric mean of the several levels sampled) and regressed based on temperature, pH, DO and also time. In order to check for non-linear association, scatter plots of $k_p$ against these parameters were also done. The only evident non-linear association was between $k_p$ and time (exponential decrease). Thus, a logarithmic [$y = \ln(k_p)$] transformation was applied to the $k_p$ data. Experiments from Group A were also analysed as one experiment (EAT), since their resting phases can be considered replicates. Stepwise multiple regression, with $p$-to-enter of 0.05 and $p$-to-leave of 0.10, using the statistical package SPSS, was used. Table 3 presents the regression coefficients for the parameters that remained in the regression equations and the corresponding coefficients of determination ($r^2$).

In four out of eight experiments in which $k_p$ and/or $\ln(k_p)$ was significantly associated with one or more parameters, time alone, more than the other parameters, could explain the variance of $\ln(k_p)$ (99.6, 76.2, 97.8 and 99.1% for EA1, EA2, EC2 and EC3 respectively).
In the other four experiments, pH 0800 h, temperature 1500 h, DO 0800 h and Chl a (not all simultaneously) explained 95.2, 100, 97.9 and 97.1% of the variance of $k_b$. pH and Chl a presented both positive and negative regression coefficients, whereas the regression coefficient for DO was negative. Temperature presented a significant positive regression coefficient, but in only one out of the eight experiments analysed.

In these last four experiments (EA3, EA4, EA5 and EC1) time still could explain 78.3, 96.0, 85.2 and 90.3%, respectively, of the variance of $\ln(k_b)$, in comparison to the values explained by the other parameters. Furthermore, in the more representative experiment (EAT), only time remained in the regression equation and the coefficient of determination was higher in the exponential model. Therefore, the FC decay rate in WSTR is strongly time-dependent, decreasing in an exponential manner.

Modified Chick Law

The regression equations presented in Table 3 in the form $\ln(k_b) = at + b$ can be re-arranged in the form:

$$k_b = k_{bo} e^{-\alpha t}$$

where: $k_b$ is the FC decay rate (time units)$^{-1}$; $k_{bo}$ is the initial FC decay rate (time units)$^{-1}$; $e$ is Euler’s number (base of Napierian logarithms); $\alpha$ is the rate at which $k_b$ decreases (time units)$^{-1}$; and $t$ is time (time units).

A modification of Chick’s law (Chick, 1908) is required for a more precise estimation of FC numbers in WSTR. If, in Chick’s law, we consider $k_b$ as a time-function rather than as a constant, we will have Eq. 2:

$$\frac{dN}{dt} = -k_{bo} e^{-\alpha t} N.$$  

Integration of Eq. 2 results in Eq. 3:

$$N = N_{o} e^{\frac{k_{bo}}{\alpha}} (1 - e^{-\alpha t}).$$

Applying the Mean Value Theorem, the mean value for $k_b$ is given by:

$$k_{bm} = \frac{k_{bo}}{\alpha} (1 - e^{-\alpha \bar{t}}).$$

Table 4 shows the regression coefficients in the form of $k_{bo}$ and $\alpha$. In addition, the time necessary for FC to reach the WHO (1989) recommendation of less than $10^3$ cfu/100 mL and $k_{bm}$ for the first 25 days of resting (time enough for FC to reach $10^3$ cfu/100 mL) are also shown. Correlation analyses involving $k_{bo}$, $k_{bm}$ (for the first 25 days of resting) and $\alpha$ against all the environmental parameters and time were done, but no significant correlation coefficients were found.

Figure 1 show the scatter plot of $k_b$ against time, the line of best fit and the corresponding 95% confidence limits lines for EAT. Figure 2 shows the FC decay during EA3.

The effect of sunlight on FC decay rate in WSTR

The effect of sunlight on FC decay rate was assessed by the comparison between EC1 (3.40 m deep) versus EC2 (3.40 m deep, covered), and EC3 (2.00 m deep) versus EC4 (2.00 m deep, covered).
The mean values of \( k_b \) in the period necessary for FC to reach \( 10^3 \text{ cfu/100 mL} \) in EC1 (21.1 days) were computed from Eq. 4 for EC1 and EC2, resulting in 0.400 and 0.338 d\(^{-1}\), respectively. Thus, light-related effects (EC1 – EC2) accounted for 15.5% of the total (EC1) FC decay rate. The decay rate in the dark (EC2) accounted for the remaining fraction (84%). The time, from the beginning of resting, for FC to reach \( 10^3 \text{ cfu/100 mL} \) in EC1 was 64% of that in EC2.

The difference in time for FC to reach \( 10^3 \text{ cfu/100 mL} \) using Eq. 3 could not be computed for EC3 versus EC4, since the regression coefficients for this last experiment were not significant at the level of 5%. However, this comparison was made by means of exponential interpolation of FC numbers between the day immediately before and that on which FC numbers were less than \( 10^3 \text{ cfu/100 mL} \). The time, from the beginning of filling, for FC to reach \( 10^3 \text{ cfu/100 mL} \) in EC3 (12.3 days) was 47% of that in EC4 (26.0 days).

### Table 4: FC decay in the WSTR studied at EXTRABES

<table>
<thead>
<tr>
<th>Exp.</th>
<th>( k_{bo} ) (d(^{-1}))</th>
<th>( \alpha ) (d(^{-1}))</th>
<th>( k_{bm} ) (d(^{-2}))</th>
<th>No (cfu/100 mL)</th>
<th>Time for FC to reach ( 10^3 \text{ cfu/100 mL} ) (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>from the beginning of resting</td>
<td>from the beginning of filling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EA1</td>
<td>0.462</td>
<td>0.0417</td>
<td>0.287</td>
<td>( 1.80 \times 10^6 )</td>
<td>27.0</td>
</tr>
<tr>
<td>EA2</td>
<td>0.344</td>
<td>0.0170</td>
<td>0.280</td>
<td>( 2.21 \times 10^6 )</td>
<td>28.2</td>
</tr>
<tr>
<td>EA3</td>
<td>0.523</td>
<td>0.0467</td>
<td>0.309</td>
<td>( 1.10 \times 10^6 )</td>
<td>21.0</td>
</tr>
<tr>
<td>EA4</td>
<td>0.546</td>
<td>0.0431</td>
<td>0.334</td>
<td>( 1.71 \times 10^6 )</td>
<td>20.6</td>
</tr>
<tr>
<td>EA5</td>
<td>0.420</td>
<td>0.0306</td>
<td>0.294</td>
<td>( 2.54 \times 10^6 )</td>
<td>27.7</td>
</tr>
<tr>
<td>EC1</td>
<td>0.807</td>
<td>0.0766</td>
<td>0.359</td>
<td>( 4.57 \times 10^6 )</td>
<td>21.1</td>
</tr>
<tr>
<td>EC2</td>
<td>0.502</td>
<td>0.0403</td>
<td>0.316</td>
<td>( 9.76 \times 10^6 )</td>
<td>33.2</td>
</tr>
<tr>
<td>EC3</td>
<td>0.909</td>
<td>0.0629</td>
<td>0.458</td>
<td>( 5.83 \times 10^6 )</td>
<td>14.6</td>
</tr>
<tr>
<td>EAT</td>
<td>0.447</td>
<td>0.0350</td>
<td>0.298</td>
<td>( 1.80 \times 10^6 )</td>
<td>25.2</td>
</tr>
</tbody>
</table>
Since micro-invertebrates were absent in the reservoirs, due to the predominantly anaerobic environment, and considering that FC sedimentation (adsorption onto settleable solids) during the resting phase was minimal or even nil, most of FC decay measured in the resting phase was due to natural die-off.

It was found in this study that, as the reservoir depth decreased from EAT to EC1 and again to EC3, the mean FC decay rate for the first 25 days, for example, increased from 0.298, 0.359 and 0.458 d\(^{-1}\). Figure 3 shows the time for FC to reach 10\(^{3}\) cfu/100 mL for any reservoir depth. Due to the limited number of depths studied (\(n = 3\)), the level of significance of line of best fit (Eq. 5) was only 11%. However, as the depth decreases, an increase in the number of reservoirs (i.e., increase in an area) is required for any given applied organic loading.

\[
RT = 8.896 \ln(D) + 9.065 
\]  
(5)

where: \(RT\) is the resting time (d), and \(D\) is the reservoir depth (m).

Sequential batch-fed WSP
The die-off rates of FC in batch-fed WSTR were found to be similar to those reported in the literature for WSP in series (de Oliveira et al. 1996). Therefore, batch-fed reservoirs can be considered as a treatment unit rather than a storage one. In this case, they can be operated as sequential batch-fed WSTR without provision for the storage of the wet-season wastewater (like ponds). Such operation will be referred herein to as sequential batch-fed WSP (SBFWSP)

SBFWSP are particularly applicable when FC removal is required, since the resting phase, following the idea presented by Mara & Pearson (1992) for WSTR, avoids the mixing of fresh and treated wastewater and consequently FC contamination of the latter by the former. The resting phase also guarantees a minimum age for the effluent, so permitting greater reliability in predicting the effluent bacteriological quality. When WSP are operated in a continuous regime, short-circuiting inside the pond mixes fresh and treated wastewater, so degrading the effluent bacteriological quality. Operation in series improves the hydraulic regime, but a minimum effluent age cannot be guaranteed as in the case of sequential batch-fed operation.

Adopting a \(\lambda_s\) of 659 kg BOD\(_5\)/ha.d, the highest employed in this study, a BOD\(_5\) of 116 mg/L (the upper 95% confidence limit for the APE) and a given flow rate \(F\) (m\(^3\)/d), the area of only one pond in a sequential batch-fed WSP system would be 1.76\(F\). The volume and filling time can be subsequently computed by multiplying the area by the depth and by dividing the volume by the flow rate, respectively.

For the SBFWSP studied herein, the shallowest one presented the lowest volume but also the highest area, whereas the deepest presented the highest volume but also the lowest...
Therefore, the best SBFWSP depth can only be defined by a financial analysis, details of which are given in Athayde Júnior (1999). The series of WSP already studied at EXTRABES in which FC reached $10^3$ cfu/100 mL (Silva, 1982; de Oliveira, 1990; de Oliveira et al., 1996; Pearson et al., 1996) were also included in the analysis to compare different operational regimes.

In general, the series of WSP presented much better results. Nevertheless, the depths of the SBFWSP (2.00–6.50 m, originally conceived as reservoirs) were much higher than those of the WSP operated in series (0.82–2.20 m), so that this comparison lacks credibility.

For a better comparison, the filling ($1.76D$) and resting (Eq. 5) times of a SBFWSP system were computed for the depths of each of the series of WSP. In three out of five systems compared, batch-fed operation was a better option than the series of ponds. Although WSP in series had a higher benefit/cost ratio in two of the five cases compared, the effluent age (a crucial factor in determining the bacteriological quality) of a series of WSP cannot be guaranteed as in the case of batch-fed operation, when the wastewater age can be exactly computed and FC numbers predicted more reliably.

Further investigation on shallow ponds, both batch-operated and in series, may result in more conclusive results. The use of higher loadings will make the sequential batch-fed WSP more cost effective as their volume will be reduced (reduced filling time). Higher loadings applied to a series of WSP does not necessarily imply a lower volume and area, since the hydraulic regime may be negatively affected. Further investigation is also required on this point.

**Provision of additional volume for the winter flow**

If additional volume (and area) to store the winter effluent is provided, costs and evaporation losses will be greater, but so will be the area irrigated and therefore the amount of crops produced. Therefore, it is a matter only to compare the pay-back of additional crops produced against the additional investment due to the additional volume and area, plus the higher operation and maintenance cost of the treatment plant.

To treat the whole year’s wastewater and store the winter effluents, the hybrid WSP-WSTR system proposed by Mara et al. (1996) can be employed. The single batch-fed reservoir does not need to work as a treatment unit (only as a storage one), since the wastewater is already treated in the WSP system, and thus a resting time is not necessary. Since the reservoir works as a storage unit, it should be as deep as feasible to minimise losses due to evaporation. A 10 m deep reservoir was considered herein. The economical viability of the hybrid WSP-WSTR system was compared to that of a series of WSP (details of the financial analysis are given in Athayde Júnior, 1999).

Figures 4 and 5 show the benefit/cost ratios and the annual net returns for the hybrid WSP-WSTR and the WSP systems for the duration of the rainy season. In places where the rainy season is more than 6 months, there should be enough water stored in reservoirs so that wastewater-based irrigation would not be necessary. Nevertheless, to compensate for evaporation and seepage, rainy seasons up to 8 months were considered.

For rainy seasons between 3 and 5 months (irrigation seasons between 7 and 9 months) and land price and available wastewater flow herein considered, the series of WSP were the most viable option, with a benefit/cost ratio of 28 compared to around 22 for the hybrid WSP-WSTR system. Despite the higher net annual return of the hybrid WSP-WSTR (US$ 698,445 for rainy season of 4 months, for instance) compared to that of the WSP system (US$ 440,436), the higher benefit/cost ratio of the latter means that, provided there is wastewater available for irrigation during the dry season at other locations, 2.08 times more wastewater could be treated in WSP (construction cost of US$ 158,523) and reused in the dry season using the construction costs of the hybrid WSP-WSTR system (US$ 330,069 for...
a rainy season of 4 months for example) corresponding to a net annual return of 2.08 $\times$ US$ 440,436 = US$ 917,055.

Therefore, only when no more wastewater is available for irrigation without storage of the winter effluent, should the addition of a reservoir to a series of WSP (i.e. forming the hybrid WSP-WSTR system) be considered. In this case, the net return is US$ 0.17–0.22 (for rainy season ranging from 3 to 5 months) per cubic metre of wastewater available.

**Conclusions**

FC die-off during the WSTR filling phase is very reduced, suggesting that these reactors should be filled as quickly as possible (adopting a BOD surface loading up to 659 kg BOD$_5$/ha.d and possibly more). During the resting phase, the FC die-off decreases exponentially for which a modified Chick’s law was developed. The initial value for FC die-off rate decreases as the WSTR depth increases and consequently shorter resting times are needed in shallow reservoirs. As the WSTR depth ranged from 2.00 to 6.50 m, the resting time for FC to reach $10^3$ cfu/100 mL varied from 15 to 25 days. The natural (time-related) fraction of the FC die-off rate is more important, being responsible for 85% of the total FC die-off rate in a 3.40 m deep reservoir, for example, although this increases as the WSTR depth decreases.

Sequential batch-fed WSP are in general a lower cost option than WSP operated in series. A study on shallow ponds, operated both as batch-fed units and in series may produce more conclusive results.

When provision of storage volume for the winter effluents is considered, a WSP system presents a higher benefit/cost ratio than a hybrid WSP-WSTR system, but the adoption of the latter can double the net annual return for a rainy season of 5 months, for instance.
a hybrid WSP-WSTR system is used, the net return would be US$ 0.17–0.22 per cubic metre of available wastewater, depending on the length of the rainy season considered (3–5 months), compared to US$ 0.12 for the WSP system alone.

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