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REVISITING THE INFLUENCE OF LOADING ON ORGANIC MATERIAL REMOVAL IN PRIMARY FACULTATIVE PONDS

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Abstract - This paper investigated the influence of organic loading on BOD and COD removal in primary facultative ponds. The study was based on six full-scale pond plants in which average removals of unfiltered biochemical oxygen demand (BOD) and chemical oxygen demand (COD) were 72 and 50%, respectively. For filtered samples, the removals were 89 and 83%, respectively. First-order removal rates assuming ideal hydraulic patterns (completely mixed and plug-flow) decreased with increments in the mean hydraulic retention time (HRT). Reduction in organic loading also caused a decrease in removal rates. The results emphasized that HRT and surface organic loading are more reliable to estimate first-order removal rates than traditional Arrhenius-style equations. Thus, HRT and surface organic loading can be used to compute more realistic first-order removal rates and surface removal rates. An alternative design procedure based on HRT and surface organic loading was proposed and demonstrated.

Keywords: Primary facultative ponds; Removal of organic material; Design model.

INTRODUCTION

In waste stabilization pond technology, primary facultative units are the most used and investigated. They can be designed as single cells or as part of a pond series. Analytical models for the design of primary facultative ponds are based on first-order kinetics. An ideal hydraulic pattern is assumed that may be either completely mixed (Equation 1) or plug-flow (Equation 2) (USEPA, 1983; Preul and Wagner, 1987; Yánez, 1993; von Sperling, 2002).

$$L = Lo/(1 + k.HRT) \quad (1)$$

$$L = Lo.e^{-k.HRT} \quad (2)$$

where: L and Lo are the effluent and influent biochemical oxygen demand, BOD (mg/L), respectively, k is the first-order removal rate (day^{-1}), and HRT is the mean hydraulic retention time (days).

The k value is temperature (T) dependent and the appropriate correction is obtained through Arrhenius-style equations. For completely mixed conditions, Mara (1976) suggested Equation 3, while for plug-flow Equation 4 is recommended by USEPA (1983).

$$k = 0.3(1.05)^{T-20} \quad (3)$$

$$k = 0.71(1.09)^{T-20} \quad (4)$$

Thirumurthi (1974), Mara and Silva (1979) and Uhlmann (1979) observed that reaction rates also varied with organic loading and decreased as loading was lowered. Ellis and Rodrigues (1995) reported from full-scale ponds k values ranging from 0.22 to

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0.54 day^{-1}, at 20° C. In their own findings, the mean k value was 0.168 day^{-1} for unfiltered samples at 20°C. In filtered samples after algae removal they found a first-order removal rate of 0.327 day^{-1}. These authors recommended that a k value of 0.3 day^{-1} at 20°C, from Equation 3, would be more appropriate for filtered BOD. For unfiltered samples, a more realistic k value would be 0.201 day^{-1}. They also suggested an estimate of k (day^{-1}) as a function of organic loading applied to the pond (λs in kg BOD/ha.day) according to the equation below.

$$k = 2.622\text{x}10^{-3}\,\lambda s - 0.194 \qquad (5)$$

Actually, pond flow is neither completely mixed nor plug-flow. The dispersed flow is more adequate to represent the hydraulic pattern, as initially observed by Thirumurthi (1969). This approach is based on the Wehner-Wilhelm kinetic equation. However, there is a drawback due to the lack of data from field studies. The use of the dispersion-based model is debatable because extensive investigation would be required to obtain reliable figures. A broad application is limited by a number of factors such as unsteady flow, wind, and inlet and outlet structures that may significantly influence dispersion in ponds.

According to Juanico (1991), the plug-flow model is more representative of bacterial removal in contrast with BOD removal, which is more likely to approach completely mixed conditions. This explains why investigations on the influence of hydraulic pattern have focused on coliform removal and with good results (e.g. Lloyd and Vorkas, 1999; Shilton and Harrison, 2003; von Sperling, 2003; Shilton and Mara, 2005; Bracho et al., 2006).

Mara and Pearson (1986) and Mara et al. (1992) stated that limitations of "rational" methods based on first-order kinetics led to empirical procedures based on ambient temperature. Mara (1987) proposed a commonly applied model for the computation of the maximum allowable organic loading in facultative ponds (Equation 6).

$$\lambda s = 350(1.107-0.002T)^{T-25} \qquad (6)$$

where: λs is the maximum allowable surface loading applied to the pond (kg BOD/ha.day) and T is the average temperature of the coldest month (°C).

A properly designed primary facultative pond has a performance for BOD removal ranging from 70 to 80% for unfiltered samples and about 90% for filtered samples (Mara, 1997). Nevertheless, there is still a debate on design models that would better represent reality and couple with the performance of full-scale systems. Thus, our paper addresses this discussion and takes into account findings from full-scale pond systems. The purpose is to provide a more feasible and dependable approach for the design of primary facultative ponds.

MATERIALS AND METHODS

Six full-scale primary facultative ponds (PFPs) located in Fortaleza (38° 32' W; 3° 43' S, 15.5 m above the sea level), in Northeast Brazil, were investigated during 28 weeks in 2007. These pond plants have been operating for 22 years on average. Their original design characteristics are given in Table 1.

Raw wastewater and treated effluent samples were collected weekly at 10:00 AM. Flow measurements were performed with a clockwork device at the pumping station of each plant. The following parameters were analyzed in the raw wastewater: temperature, pH, biochemical oxygen demand (BOD) and chemical oxygen demand (COD). In the treated effluent these parameters were complemented with dissolved oxygen (DO), filtered BOD (BODf) and filtered COD (CODf). The analytical procedures followed the methods described in APHA (1992).

Table 1: Design characteristics of the primary facultative ponds.

Pond system	HRT (days)	λs (kg BOD/ha.day)	Volume (m^3)	Width to length Ratio	Mean depth (m)
PFP_1	26.9	178	22194.0	1:1.52	1.7
PFP_2	62.0	128	168400.0	1:1.52	2.0
PFP_3	25.7	261	25710.4	1:2.10	1.6
PFP_4	25.0	230	51000.0	1:2.04	1.7
PFP_5	22.3	283	45736.8	1:1.78	1.7
PFP_6	18.8	287	17910.0	1:1.84	1.8

RESULTS AND DISCUSSION

Temperature of the influents to the pond systems ranged from 22.0 to 26.2°C (mean of 24.9°C), while in the treated effluents it varied from 24.9 to 29.1°C (mean of 27.2°C). The pH of the raw wastewater was around neutral (7.11 ± 0.19). Unfiltered BOD and COD showed typical values of domestic wastewaters: 430 ± 150 mg/L and 707 ± 278 mg/L, respectively.

PFP_2 and PFP_4 ponds had HRTs similar to those in the design assumptions shown in Table 1. However organic loadings in these ponds were above design (14 and 32%, respectively). The other plants had higher HRTs (78.5 ± 44.2 days) and BOD loadings were 41 ± 19% below the values assigned in the original designs. Uncompleted connections of the buildings to the sewerage network and low *per caput* wastewater contributions may have caused lower influent flow rates to the plants, as suggested by Campos and von Sperling (1996). Table 2 shows the actual operational performance of the pond systems investigated.

Unfiltered BOD removal was at the lower limit (around 70%) mentioned in the literature (Mara et al., 1992; Mara, 1997). Consequently, unfiltered COD removal was also at the lower limit (around 50%). Concentrations of unfiltered BOD and COD in the treated effluents of the pond systems were 121 ± 36 mg/L and 343 ± 115 mg/L, respectively. Filtered samples (BODf and CODf) represented 39 ± 15% and 36 ± 18% of the respective unfiltered BOD and COD. The performance regarding filtered samples was in accordance with a number of studies (Bucksteeg, 1987; Mara et al., 2001; Abis and Mara, 2005).

Surface removal rates of unfiltered and filtered BOD and COD correlated positively with the organic loading applied to the ponds (Figures 1 and 2). On the other hand, neither width to length ratio nor depth of the ponds showed a significant correlation with organic material removal.

Mean dissolved oxygen concentration in the treated effluents was 4.3 ± 3.6 mg/L. The highest values were observed in PFP_6 (7.4 ± 3.5 mg/L), while the lowest were in PFP_2 (2.1 ± 1.3 mg/L). Average pH in pond effluents was 7.80 ± 0.21. It was higher in PFP_3 (8.04 ± 0.29) and lower in PFP_2 (7.53 ± 0.29).

There was a positive correlation between pH and DO (r = 0.7191 at the 0.05 level of significance). Positive correlations of pH (r = 0.7638) and DO (r = 0.6150) were also observed in relation to surface CODf removal rate.

Table 2: Operational performance of the primary facultative ponds.

Pond system	HRT (days)	λs_{BOD} (kg/ha.day)	λs_{COD} (kg /ha.day)	Removal %			
				BOD	BODf	COD	CODf
PFP_1	51.8	117	188	71	87	55	82
PFP_2	64.0	148	225	73	89	48	83
PFP_3	80.7	80	145	71	90	52	86
PFP_4	25.2	338	501	73	90	46	78
PFP_5	41.5	130	270	63	88	51	83
PFP_6	139.9	65	105	75	89	45	87

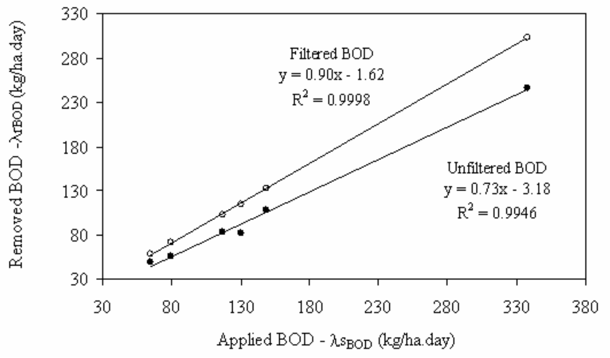

Figure 1: Surface BOD removal rates as a function of loading.

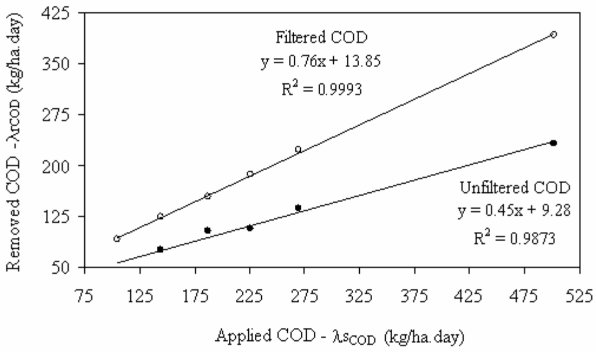

Figure 2: Surface COD removal rates as a function of loading.

The hydraulic retention times in the pond systems influenced pH and DO values, with correlation coefficients of 0.6846 and 0.6882 respectively (at the 0.05 level of significance). This was similar to findings of Ceballos et al. (1996). These authors stated that HRT and loading impact algal dynamics and nictemeral variations that influence DO and pH.

The computed first-order removal rates based on ideal hydraulic flow are shown in Table 3. The values of the k for unfiltered BOD were lower than those calculated with the Arrhenius-style equations. For the completely mixed condition (Equation 3), the corrected value of k would vary from 0.381 to 0.468 day^{-1} (mean of 0.426 day^{-1} at 27.2°C), for a temperature ranging from 24.9 to 29.1°C. For the case of the plug-flow condition (Equation 4), the adjusted k value would vary from 1.083 to 1.555 day^{-1} (mean of 1.320 day^{-1}), in the same temperature range. These numbers are too high even if compared to k rates computed for filtered samples.

Hydraulic retention time and surface organic loading correlated with first-order reaction rates (at the 0.05 level of significance). Tables 4 and 5 provide empirical models that could be used for design ends.

Correlation discrepancies are not significant unless they are seen under a more detailed statistical perspective. The discussion does not address which ideal hydraulic regimen is more representative, but the fact that higher HRTs and consequent lower surface organic loadings cause a decrease in first-order removal rates. Also, pond performance will not increase with a longer HRT or lower organic loading. This will not result in an effluent with less organic content.

The fact is that the correction of first-order removal rates with Arrhenius-style equations produces unrealistic numbers. For design purposes, a reasonable approach is initially to compute the maximum allowable BOD loading (λs). After that, it is necessary to define geometric elements (length, width and depth) and compute the HRT. Then, either λs or HRT from Tables 4 and 5 may be used to calculate a more realistic k. The final effluent BOD is then computed from Equations 1 or 2, according to the initial assumption for a chosen hydraulic regimen.

If the designer wishes to estimate COD in the effluent, it is necessary to know the BOD/COD ratio in the influent and make the appropriate replacements. In domestic wastewaters, this ratio is around 0.5 (Metcalf and Eddy, 1991). The process also allows one to estimate organic content in filtered samples. Figure 3 represents this proposed stepwise approach.

Table 3: First-order removal rates (day^{-1}) in the primary facultative ponds.

Statistic parameter	Completely mixed				Plug-flow			
	BOD	BODf	COD	CODf	BOD	BODf	COD	CODf
Mean	0.048	0.159	0.019	0.091	0.024	0.043	0.013	0.034
Min.	0.022	0.059	0.006	0.046	0.010	0.016	0.004	0.014
Max.	0.106	0.351	0.034	0.144	0.052	0.091	0.025	0.061
CV (%)	62	64	52	37	60	60	53	48

Table 4: First-order removal rates in primary facultative ponds as a function of HRT.

Removal parameter	Completely mixed	Plug-flow
BOD	$k = 1.3401HRT^{-0.851}$ $R^2 = 0.8824$	$k = 0.8719HRT^{-0.9141}$ $R^2 = 0.9610$
BODf	$k = 7.6572HRT^{-0.9889}$ $R^2 = 0.9750$	$k = 2.1546HRT^{-0.9952}$ $R^2 = 0.9958$
COD	$k = 1.1918HRT^{-1.0476}$ $R^2 = 0.9360$	$k = 0.7883HRT^{-1.0353}$ $R^2 = 0.9649$
CODf	$k = 1.2396HRT^{-0.6573}$ $R^2 = 0.9667$	$k = 0.9307HRT^{-0.8397}$ $R^2 = 0.9954$

Table 5: First-order removal rates in primary facultative ponds as a function of surface loading.

Removal parameter	Completely mixed	Plug-flow
BOD	$k = 0.0003\lambda s_{BOD} + 0.0043$ $R^2 = 0.9723$	$k = 0.0001\lambda s_{BOD} + 0.0031$ $R^2 = 0.9594$
BODf	$k = 0.001\lambda s_{BOD} + 0.0132$ $R^2 = 0.9464$	$k = 0.0003\lambda s_{BOD} + 0.0066$ $R^2 = 0.9142$
COD	$k = 0.0172Ln(\lambda s_{COD}) - 0.0727$ $R^2 = 0.8305$	$k = 0.0125Ln(\lambda s_{COD}) - 0.0536$ $R^2 = 0.8798$
CODf	$k = 0.0601Ln(\lambda s_{COD}) - 0.2305$ $R^2 = 0.9092$	$k = 0.029Ln(\lambda s_{COD}) - 0.1213$ $R^2 = 0.9387$

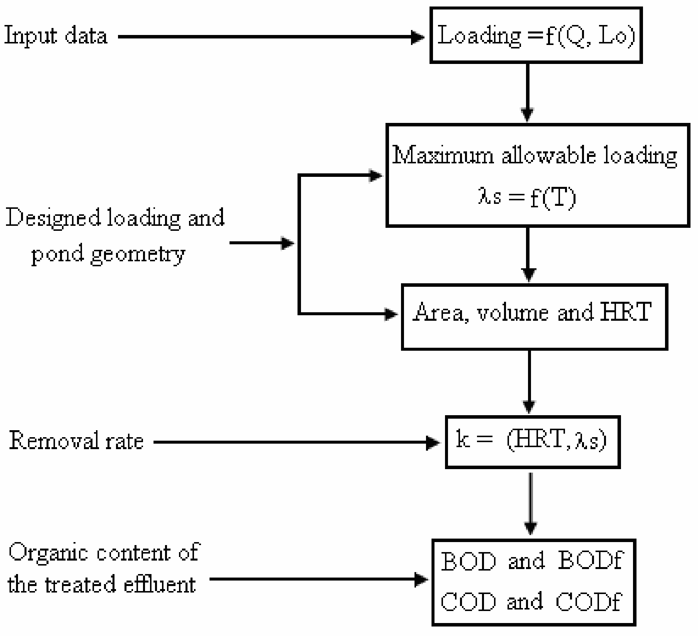

Figure 3: A stepwise approach for the design of primary facultative ponds.

As an example, let us assume a domestic influent with a flow rate of 1000 m^3/day and a BOD of 400 mg/L (therefore COD is 800 mg/L). The average ambient temperature during the coldest month is 20°C, the hydraulic regimen is assumed to be completely mixed and the pond depth is 2.0 m. Following the proposed method, the calculation procedure is:

i) Organic loading to be treated (BOD x Flow rate)

- = 0.4 $kg/m^3 \times 1{,}000\ m^3/day$ = 400 kg BOD/day (800 kg COD/day)

ii) Maximum allowable loading (according to Mara, 1987)

- $\lambda s = 350(1.107-0.002 \times 20)^{20-25} = 253$ kg BOD/ha.day (506 kg COD/ha.day)

iii) Pond area, volume and HRT

- Pond area = Organic loading to be treated/λs = (400 kg BOD/day)/(253 kg BOD/ha.day) = 1.58103 ha $\times$ 10,000 m^2/ha = 15,810.3 m^2
- Pond volume = Pond area $\times$ Depth = 15,810.3 m^2 x 2.0 m = 31,620.6 m^3
- HRT = Volume/Flow rate = 31,620.6 m^3/(1,000 m^3/day) = 31.62 days

iv) First-order removal rates (for completely mixed, Table 5)

- BOD → k = $0.0003 \times (253$ kg BOD/ha.day) + 0.0043 = 0.080 day^{-1}
- BODf→ k = $0.001 \times (253$ kg BOD/ha.day) + 0.0132 = 0.266 day^{-1}
- COD → k = $0.0172 \times \mathrm{Ln}(506$ kg COD/ha.day) – 0.0727 = 0.034 day^{-1}
- CODf→ k = $0.0601 \times \mathrm{Ln}(506$ kg COD/ha.day) – 0.2305 = 0.144 day^{-1}

v) Organic content in the treated effluent

- BOD → L = 400 mg/L/(1+0.080 $day^{-1} \times$ 31.62 days) = 113 mg/L
- BODf→ L = 400 mg/L/(1+0.266 $day^{-1} \times$ 31.62 days) = 42 mg/L
- COD → L = 800 mg/L/(1+0.034 $day^{-1} \times$ 31.62 days) = 386 mg/L
- CODf→ L = 800 mg/L/(1+0.144 $day^{-1} \times$ 31.62 days) =144 mg/L

The computation above resulted in removal efficiencies of 72, 90, 52 and 82% for BOD, BODf, COD and CODf, respectively. This performance is conservative, but similar to numbers from full-scale plants (von Sperling et al., 2004; Oliveira et al., 2006).

For a first-order removal rate of 0.3 day^{-1} from Equation 3, the final unfiltered BOD would be 38 mg/L (90% removal). This result is too "good" and inconsistent with reality. Also, there is not an estimate of filtered BOD and COD concentrations in the treated effluent.

CONCLUSIONS

The six full-scale primary facultative ponds showed operational conditions different from the original designs. Performance of the pond systems were at the lower limit of the range indicated by the literature. Nevertheless, it was satisfactory and representative of reality, since these plants have been operating for over two decades.

High HRT and consequent low surface loading resulted in smaller first-order removal rates compared to the adjusted values from usual Arrhenius-style equations. Also, surface removal rates decreased as loading decreased and HRT increased.

The traditional design procedure based on the first-order removal rate provides unrealistic figures. At the same time, a rough empirical estimate of the pond performance is not a good engineering practice. Thus, an alternative design procedure was proposed, leading to a more dependable figure for organic material removal in primary facultative ponds.

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