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DEVELOPMENT AND EVALUATION OF A RADIAL ANAEROBIC/AEROBIC REACTOR TREATING ORGANIC MATTER AND NITROGEN IN SEWAGE

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Abstract - The design and performance of a radial anaerobic/aerobic immobilized biomass (RAAIB) reactor operating to remove organic matter, solids and nitrogen from sewage are discussed. The bench-scale RAAIB was divided into five concentric chambers. The second and fourth chambers were packed with polyurethane foam matrices. The performance of the reactor in removing organic matter and producing nitrified effluent was good, and its configuration favored the transfer of oxygen to the liquid mass due to its characteristics and the fixed polyurethane foam bed arrangement in concentric chambers. Partial denitrification of the liquid also took place in the RAAIB. The reactor achieved an organic matter removal efficiency of 84%, expressed as chemical oxygen demand (COD), and a total Kjeldahl nitrogen (TKN) removal efficiency of 96%. Average COD, nitrite and nitrate values for the final effluent were 54 mg.L^{-1}, 0.3 mg.L^{-1} and 22.1 mg.L^{-1}, respectively.

Keywords: Radial reactor; Fixed film; Wastewater; Nitrification; Denitrification.

INTRODUCTION

Organic matter can be removed by either anaerobic or aerobic biotechnological methods. However, in order to obtain effluent that satisfies the legal standards for discharge of organic matter, suspended solids and macronutrients, a combination of anaerobic and aerobic processes is considered economically advantageous.

In combined anaerobic/aerobic systems, a large fraction of the influent biodegradable organic matter is eliminated in the anaerobic phase. Compared with influents that are not pretreated, the effluent from this stage requires a lower oxidation capacity in the aerobic phase for both the removal of residual organic matter from the anaerobic process and nitrification. Therefore, in comparison with conventional aerobic treatment plants, combined anaerobic/aerobic sewage treatment systems have promising characteristics in terms of energy consumption and excess sludge production (Castillo et al., 1997).

In most full-scale systems designed for nitrogen removal, ammonium nitrogen oxidation followed by denitrification occurs separately in aerobic and anoxic reactors. However, in recent years, several researchers have reported on the performance of reactor configurations using conventional and new nitrogen removal processes (Górska et al., 1997; Spector, 1998; Verstraete & Philips, 1998). Thus, fixed film reactors appear to be a convenient alternative for the anaerobic biological treatment and nitrification of wastewater, allowing a high cellular retention time to be obtained, which is the most important factor affecting the stability and efficiency of biological processes.

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Vieira et al. (2000) obtained good results operating an aerobic radial reactor (ARR) designed to nitrify anaerobic reactor effluents. Given the excellent performance of the ARR, a combined anaerobic/aerobic (radial anaerobic/aerobic immobilized biomass reactor – RAAIB) reactor originally based on the radial configuration was conceived, aiming to remove both organic matter and ammonium nitrogen from sanitary wastewater.

The proposal of this study was to evaluate the technical viability of this new configuration. Accordingly, data pertaining to the reactor's performance in removing organic matter, solids and nitrogen from sewage are presented and discussed.

MATERIAL AND METHODS

The RAAIB reactor, made of acrylic with an effective height of 25 cm and a diameter of 60 cm, was built in a configuration of five concentric chambers, each with specific characteristics (Figure 1).

The third chamber contained eight porous stones distributed uniformly close to the bottom of the reactor and connected to a compressor to aerate and mix the liquid. The second and fourth chambers were packed with 10-mm-sided polyurethane foam cubes to immobilize the biomass.

The second chamber of the RAAIB reactor was inoculated with anaerobic sludge taken from an UASB reactor treating poultry slaughterhouse wastewater. The fourth chamber was not inoculated.

The wastewater was pumped by a diaphragm pump and stored in a 750 L tank. Two 2-mm mesh screens were installed inside the tank to retain the fraction of suspended solids of inappropriate dimensions for the bench-scale experimental unit. The 750 L reservoir served as an equalization tank for the influent wastewater system.

An alkaline solution with a mean concentration of 1400 mg $CaCO_3.L^{-1}$ was supplied to the third chamber to induce nitrification. The solution was added at a mean flow of 0.5 $L.h^{-1}$.

Figure 2 shows a schematic drawing of the experimental apparatus.

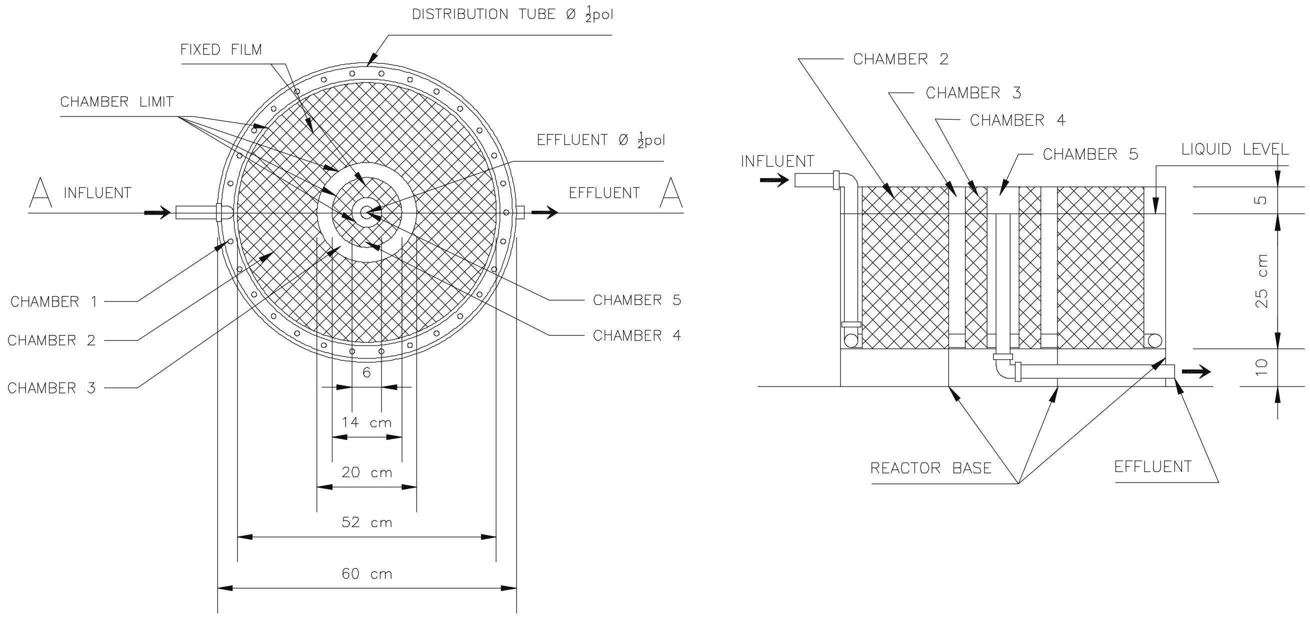
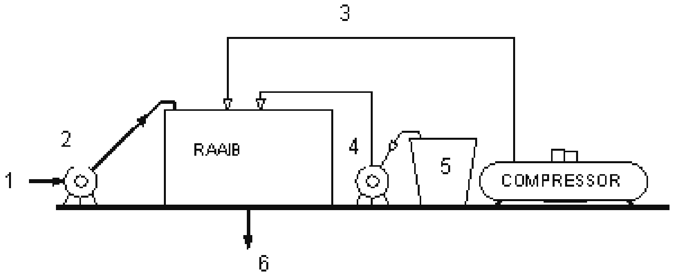


Figure 1: Scheme of the RAAIB reactor designed for the removal of organic matter from sewage and for nitrification



1. Influent wastewater;
2. Feed pump;
3. Compressed air supply to the third chamber;
4. Alkaline solution supply to the third chamber;
5. Alkaline solution container;
6. RAAIB reactor effluent

Figure 2: Schematic representation of the system:

Monitoring consisted of collecting samples at three different points: near the system influx, chamber 3 and near the effluent of the RAAIB reactor. The samples were analyzed to determine COD (chemical oxygen demand), CODf (chemical oxygen demand of filtered sample), total nitrogen, ammonium, nitrate, pH, ORP (oxidation-reduction potential), TS (total solids) and TSS (total suspended solids). The analyses were conducted according to the Standard Methods for the Examination of Water and Wastewater (1998), with the exception of TVAs (total volatile acids) and alkalinity. The TVAs were determined as acetic acid in accordance with Dilallo and Albertson (1961). Alkalinity was determined by Dilallo and Albertson’s (1961) method, modified by Ripley et al. (1986).

Table 1 lists the operating conditions of the reactor, which was operated for 123 days. During that time, the pump first used for regulating the flow experienced operational problems. This period is referred to as transitional; after that, the pump was replaced.

Table 1: Reactor operating conditions

Period	**Initial (day 0–55)**		**Transitional (day 55–93)**		**Final (day 93–123)**	
Chamber	**Flow**	**HDT ***	**Flow**	**HDT**	**Flow**	**HDT ***
(2) Anaerobic	6 L.h^{-1}	5.2 h	varied		2.0 L.h^{-1}	15.5 h
(3, 4 and 5) Mixed	6 L.h^{-1}	1.2 h	varied		2.5 L.h^{-1}	2.8 h

*HDT in relation to the functional volume.

RESULTS AND DISCUSSION

During the experimental period, the influent sewage and the system’s effluent had average temperatures of 19.2 ± 1.8°C and 20.2 ± 1.6°C, respectively.

Figures 3 and 4 show the COD values for unfiltered and filtered samples of the influent, chamber 3 and the effluent of the RAAIB. Stability in the RAAIB reactor was attained rapidly, as indicated by the low COD values for the effluent after approximately fourteen days.

After operation of the reactor has stabilized, as indicated by the establishment of COD removal and the nitrification process, under the final condition, the mean effluent COD value was 54 ± 19 mg.L^{-1}, corresponding to COD removal efficiency approximately 10% higher than the average value achieved under the first condition. The mean effluent COD$_f$ values for the two operating conditions were 80 ± 8 mg.L^{-1} (initial) and 29 ± 8 mg.L^{-1}(final).

In the initial operation, the SetS (settable solids) values were lower than 1.0 ml.L^{-1}. After the growth of filamentous organisms in chamber 3, the SetS reached approximately 90 ml.L^{-1}, indicating that the increase in COD values achieved in chamber 3 from the 25th day of operation on was due to the excessive growth of filamentous microorganisms. For this reason, the airflow was increased in the aerated chamber to increase the dissolved oxygen concentration. The increased airflow resulted in an increase in solids concentration in chamber 3, and the COD value in chamber 3 increased concomitantly. This was attributed to the resuspension of solids that had settled at the bottom of the reactor.

The COD and SetS continued to increase in chamber 3 for one week, reaching approximately 2.200 mg.L^{-1} and 125 mg.L^{-1}, respectively, after which they both rapidly declined to acceptable levels. Excessive solids were no longer detectable and the SetS concentration was 9 mg.L^{-1} on the 46th day of operation.

The simultaneous decrease in SetS and COD in chamber 3 confirmed the hypothesis that the growth of filamentous microorganisms affected the reactor performance.

The very similar values found in the TSS and VSS analyses demonstrated that the SS (suspended solids) detected in the system were basically VSS (volatile suspended solids). In most analyses, the FSS (fixed suspended solids) values were very low or even undetectable. The reduction in VSS was considerable under both operating conditions. Under the second condition, a VSS reduction efficiency of 68% was achieved, resulting in a mean effluent concentration of 19 ± 13 mg.L^{-1}. The high VSS reduction efficiency indicated that utilization of this type of reactor precludes the use of a final sedimentation unit.

Figures 5 and 6 depict the pH and total alkalinity (TA) values.

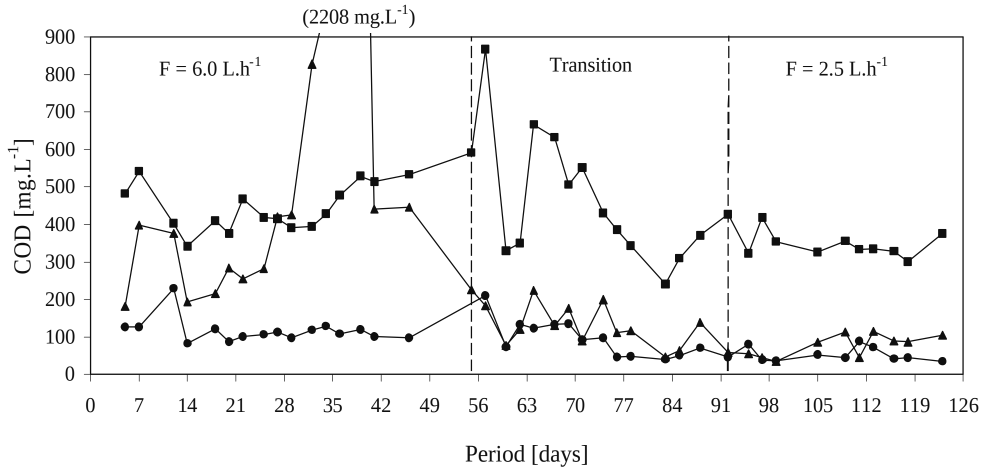


Figure 3: Values of influent ■, chamber 3 ▲ and RAAIB effluent ● COD

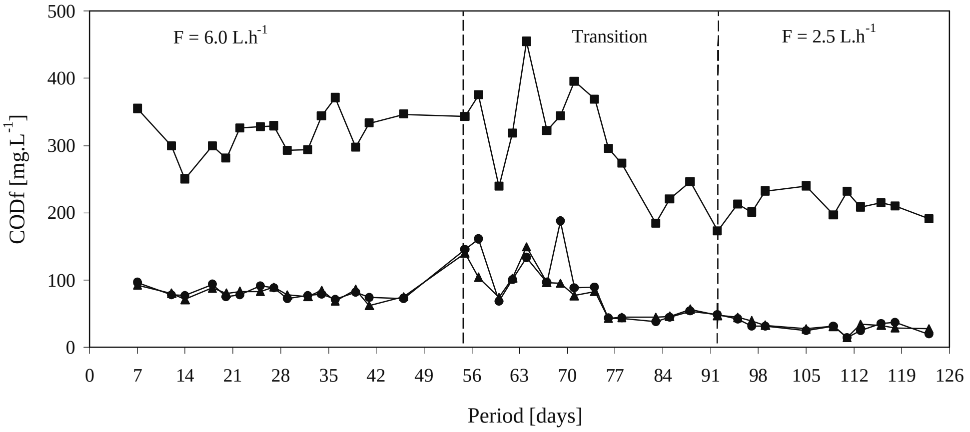


Figure 4: Values of influent ■, chamber 3 ▲ and RAAIB effluent ● CODf

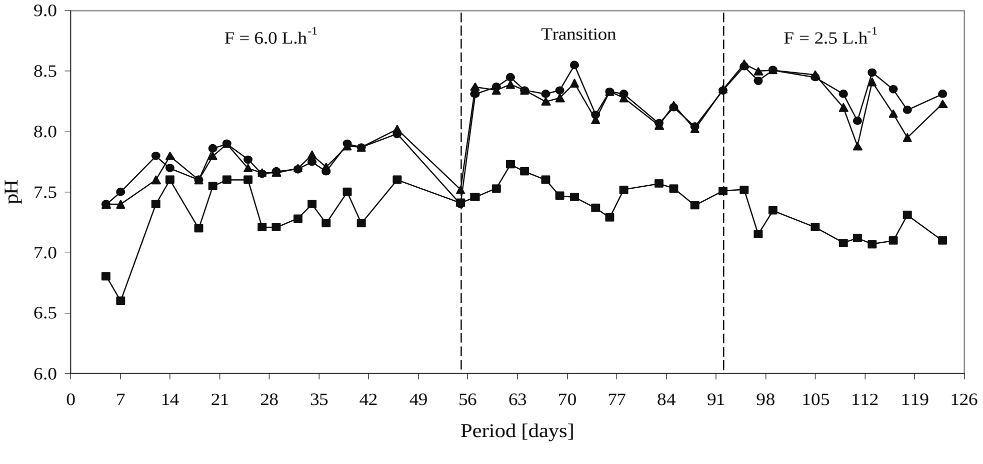


Figure 5: Values of influent ■, chamber 3 ▲ and RAAIB effluent ● pH

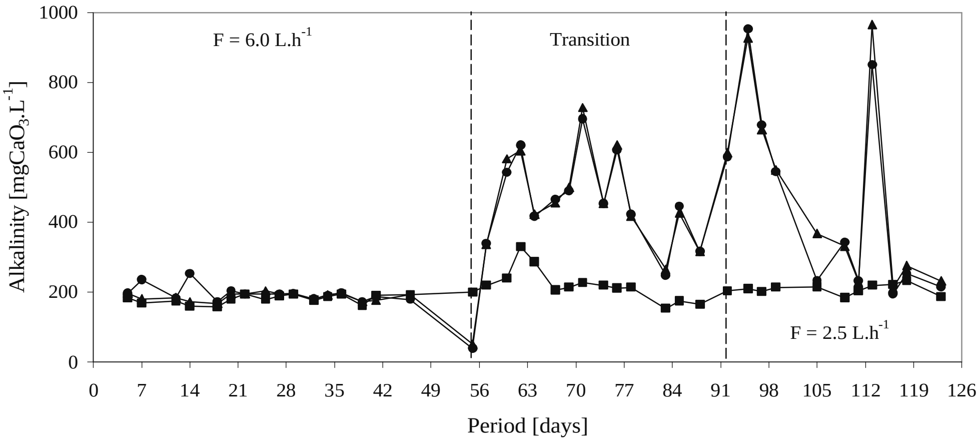


Figure 6: Values of influent ■, chamber 3 ▲ and RAAIB effluent ● bicarbonate alkalinity

The onset of nitrification and resulting alkalinity consumption resulted in a decrease in pH. The supply of sodium bicarbonate for alkalinity and the maintenance of pH at acceptable levels began on the 55th day of operation.

The dosage of bicarbonate solution was not strictly monitored since our objective was solely to ensure maintenance of the pH to prevent inhibition of the nitrification process.

The influent nitrogen was mainly N-ammon (ammonium nitrogen), as indicated by the mean N-TKN and N-ammon values of 41 ± 4 $mg.L^{-1}$ and 33 ± 4 $mg.L^{-1}$, respectively. Figure 7 contains the values of N-ammon after nitrification began in the RAAIB reactor.

N-TKN and N-ammon removal efficiencies reached mean values of 96% and >99%, respectively, after the nitrification process reached apparent dynamic equilibrium.

Figures 8 and 9 illustrate the results of the N-NO_2^- and N-NO_3^- analyses. Nitrification was considered stable only after 95 days of operation.

After stability was attained, the nitrite concentration showed mean values of 0.6 ± 0.4 $mg.L^{-1}$ in chamber 3, remaining constant at a mean value of 0.3 ± 0.3 $mg.L^{-1}$ in the RAAIB effluent. There was no accumulation of nitrite, since its concentration remained consistently below 1.0 $mg.L^{-1}$, indicating the existence of a well-established nitrite-consuming population in the reactor.

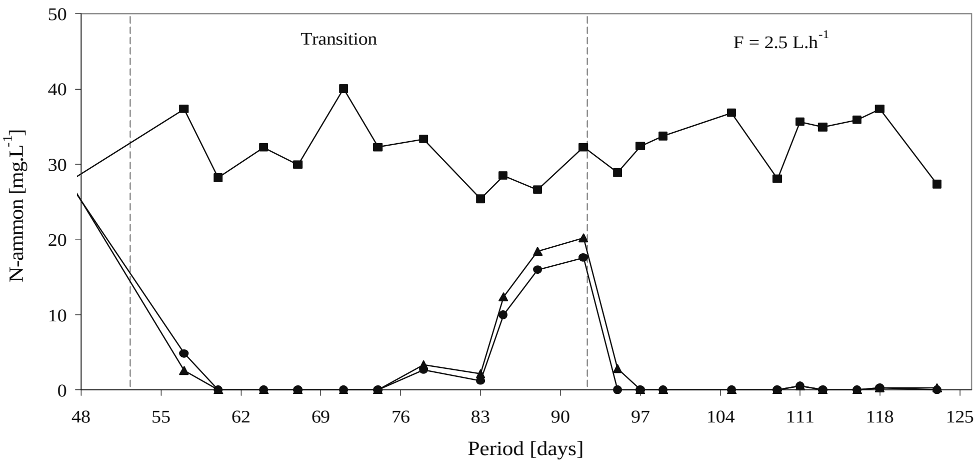


Figure 7: Values of influent ■, chamber 3 ▲ and RAAIB effluent ● ammonium nitrogen concentration

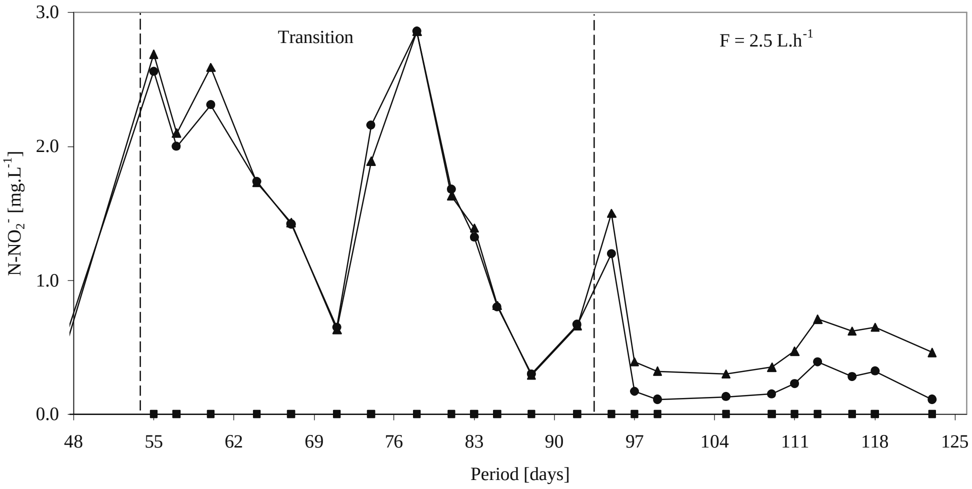


Figure 8: Values of influent ■, chamber 3 ▲ and RAAIB effluent ● nitrite concentration

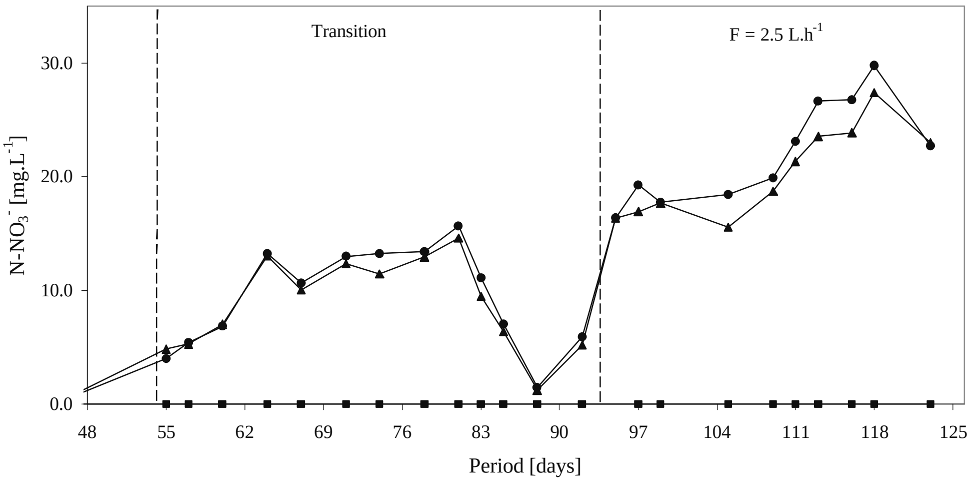


Figure 9: Values of influent ■, chamber 3 ▲ and RAAIB effluent ● nitrate concentration

Although denitrification also occurred, there were significant oscillations in the values of N-NO_3^-, with a tendency to increase in the RAAIB reactor. The apparent instability characterized by the increase in nitrate concentration in the reactor resulted from the increase in the DO concentration in chamber 5. This phenomenon started on the 105th day and continued to the end of the experiment. Simultaneous nitrification/denitrification occurred. In order to confirm this statement, a mass balance is shown in Figure 10, assuming the conversion of both nitrate and nitrite to N_2, which is based on the mean values of the nitrogen species fonud in the reactor.

The reactor proved to be efficient in removing N-ammon, whose concentration in the final effluent was lower than 1 mg.L^{-1}, reflecting in a removal efficiency of approximately 99%. The effluent N-ammon values were below the acceptable maximum value for effluent discharges, which is 5 mg.L^{-1} according to CONAMA's Resolution no. 20 (Brazil, 1986).

The oxidized forms of nitrogen (nitrate and nitrite) produced during the nitrification process with a mean concentration of 22.1 $\pm$ 4.5 mg.L^{-1} were partially removed from the RAAIB reactor. A possible explanation for this denitrification may be the occurrence of SND (simultaneous nitrification/denitrification). Reactor characteristics favor aerobic microsites, where nitrifying bacteria presumably predominate, and anoxic microsites, where denitrifying bacteria are found.

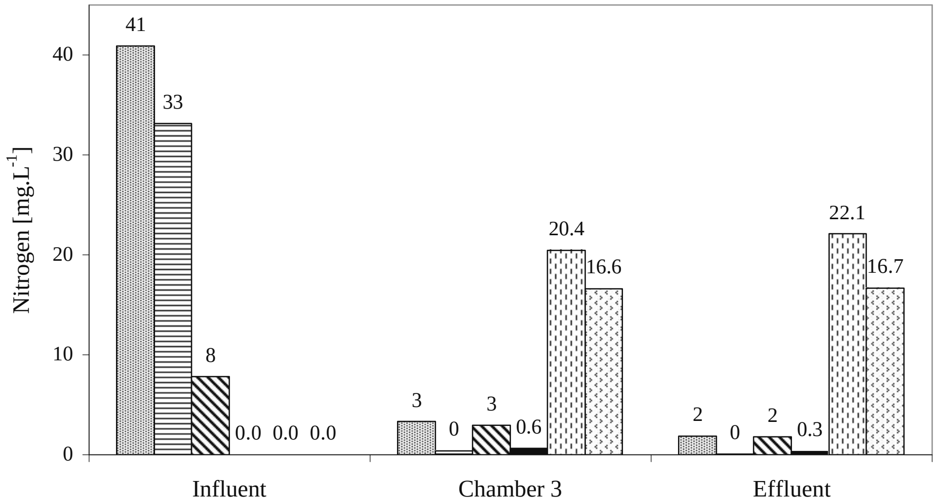


Figure 10: Nitrogen mass balance in the experimental system showing the values of N-NTK ▦, N-ammon ☰, N-org ▧, N-NO_2^- ■, N-NO_3^- ░ and N_2 ░

The ORP may serve as an indicator of the microbial processes occurring in the biofilm. The ORP values measured in the nitrified region of the RAAIB reactor were lower than those reported by Bishop and Yu (1999), who obtained positive values ranging from 300 to 400 mV, which were measured with microelectrodes at the interface between the substratum and the biofilm. These low ORP values probably resulted from the occurrence of several physicochemical and biological processes at the measuring point, probably including denitrification.

An ORP profile (Figure 11) was obtained on the 100th day of operation. In chamber 1 and in the initial portion of chamber 2, known to be a predominantly anaerobic region, the ORP value was found to be approximately -300 mV. The ORP measurements in chambers 2 and 4, close to the aeration chamber, revealed very similar values of around -170 mV. These results indicate similar microbial processes at those points, probably due to DO diffusion from chamber 3 to the others, which provided similar environments at those sites.

Table 2 summarizes the findings of each of the system's sampling points, measured under the final operating condition while nitrogen was being removed from the wastewater.

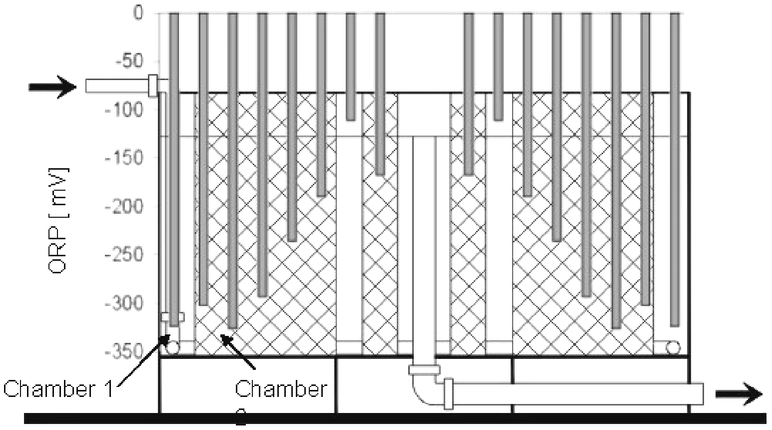


Figure 11: ORP profile for the RAAIB reactor

Table 2: Summary of the results obtained under the final operating condition of the reactor

Parameter	Unit	n°	Influent	Chamber 3	Effluent	Efficiency
Alkalinity	mgCaCO$_3$.L^{-1}	10	208 ± 15	475 ± 288	449 ± 287	-
TVA	mgHAc.L^{-1}	10	47 ± 12	22 ± 7	20 ± 5	-
COD	mg.L^{-1}	10	345 ± 33	78 ± 30	54 ± 19	84 %
CODf	mg.L^{-1}	10	214 ± 16	31 ± 8	29 ± 8	86 %
N-NTK	mgN.L^{-1}	9	41 ± 4	3 ± 3	2 ± 2	96 %
N-ammon	mgN.L^{-1}	10	33 ± 4	≤ 1	≤ 1	> 99 %
N-org	mgN.L^{-1}	9	7 ± 3	3 ± 3	2 ± 2	76 %
Nitrite	mgN.L^{-1}	10	0.0 ± 0.0	0.6 ± 0.4	0.3 ± 0.3	-
Nitrate	mgN.L^{-1}	9	0.0 ± 0.0	20.4 ± 4.0	22.1 ± 4.5	-
pH	---	10	7.2 ± 0.1	8.3 ± 0.2	8.4 ± 0.1	-
TSS	mg.L^{-1}	10	74 ± 25	32 ± 19	26 ± 20	37 %
VSS	mg.L^{-1}	10	58 ± 28	30 ± 18	19 ± 13	68 %
FSS	mg.L^{-1}	10	16 ± 14	4 ± 4	9 ± 12	-

CONCLUSIONS

The reactor removed organic matter efficiently, producing mean effluent values of 54 ± 19 mg.L^{-1} and 29 ± 8 mg.L^{-1} for COD and CODf, respectively, under the final operating condition, achieving 84% and 86% efficiency rates, respectively.

The VSS reduction efficiency was 68% with a mean effluent value of 19 ± 13 mg.L^{-1}.

For removal of N-NTK, the system showed excellent results, with an N-ammon removal efficiency of more than 99%. The mean effluent value was below the method's detection limit.

In addition to the high N-ammon removal rate, the operating conditions favored simultaneous nitrification/denitrification (SND) in the RAAIB reactor during its final period of operation. This process was responsible for the partial denitrification, reaching a maximum removal rate of approximately 70%. The main reason for the decline in nitrate removal in the RAAIB reactor was the variation in DO concentration, which reached high values, thus reducing denitrification.

The RAAIB reactor performed well in the removal of organic matter and the nitrification of sewage. However, the limiting factor for HDT reduction was clearly the volume of the chamber designed for nitrification, which admitted a maximum flow of 2.5 L.h^{-1}.

The reactor is easy to operate and control. Nevertheless, further studies are required to optimize the RAAIB reactor's nitrification and denitrification processes as a function of oxygen concentration.

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NOMENCLATURE

ARR	Aerobic radial reactor
COD	Chemical oxygen demand
CODf	Chemical oxygen demand of filtered sample
DO	Dissolved oxygen
HDT	Hydraulic retention time
N-ammon	Ammonium nitrogen
N-org	Organic nitrogen
N-TKN	Total Kjeldahl nitrogen
ORP	Oxidation-reduction potential
RAAIB	Radial anaerobic/aerobic immobilized biomass reactor
SetS	Settable solids
SND	Simultaneous nitrification/denitrification
TA	Total alkalinity
TS	Total solids
TSS	Total suspended solids
TVA	Total volatile acids
UASB	Upflow anaerobic sludge blanket
VSS	Volatile suspended solids

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