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# Optimal Sequencing Batch Reactor Conditions for Greywater Nitrogen Removal

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***Abstract:*** *The Republic of Trinidad and Tobago, arguably the most industrialised country of the English-speaking Caribbean, lags behind other similarly developed countries across the world in its utilisation of wastewater treatment systems. It is common place to see greywater being disposed into municipal storm water drains, even in the capital city and the Caroni River epitomises the effects of long-term wanton disposal of wastewater, greywater included. This study assessed the nitrogen removal capability of a sequencing batch reactor (SBR) on low strength greywater. Contrary to conventional systems, non-anaerobic conditions were maintained and no external carbon was supplied. The greywater collection time was varied to allow for observation of its treatability relative to its composition and different biological solid retention times (SRT) were assessed. A maximum of 83% total nitrogen removal was attained amongst the morning samples using a 5-day SRT. A similar maximum total nitrogen removal was also attained for the afternoon samples but required a higher SRT of 7 days.*

***Keywords:*** *Aerobic, greywater, sequencing batch reactor (SBR), solid retention time (SRT), total nitrogen (TN)*

## 1. Introduction

The term greywater is used to indicate all domestic wastewater except toilet waste. In many parts of the Caribbean non-treatment and wanton disposal of wastewater have reached serious proportions. The United Nations Environment Programme has presented data which suggests that less than 10% of the sewage generated in the Caribbean is treated (Anderson, 1997). This figure is considerably less for greywater. They have further estimated that wastewater produced by 30 million people is dumped into the Caribbean Sea each year. At a rate of 265 L/person/day, (Tchobanoglous and Burton, 1991) the situation is alarming.

There is growing concern for the protection of the marine resources of the Caribbean. Coral reefs, sea grasses and mangroves have been and continue to be threatened by coastal development since much of the waste goes directly or indirectly to the sea (Hunte, 1996).

Contamination of groundwater by nitrates is common in many parts of the world. The Netherlands, Belgium, United Kingdom, Denmark, Sweden, Switzerland, United States of America, Canada, Russia, Israel and Ethiopia have all acknowledged the existence of this form of pollution (Mekenon et al., 2001). This phenomenon is not peculiar to the Caribbean, Barbados and Jamaica are among those Caribbean islands which have documented evidence of elevated nitrate concentrations in ground water. In both cases, elevated nitrate concentrations have been attributed to anthropogenic factors (Banner et al., 1994; Goreau, 1992). The ground water risk assessment for Barbados' Belle Public Water Catchment Study of 1989 revealed that the groundwater nitrate concentration in the Belle Catchment had exceeded the WHO guidelines of 10 mg/L NO3--N, although the public groundwater sources were within the limit. The report suggested that unsewered and 'in situ' sanitation of the area, combined with the encroachment of the Bridgetown suburbs onto the sheet groundwater area of the Belle Catchment has resulted in the generation of a heavy subsurface nitrate load (PAHO and WHO, 1989). The Belle Catchment, which supplies one third of Barbados' potable water has recorded nitrogen levels as high as 9.1 mg/L- NO3--N at its public supply sources (Barbados, 1997).

The vast majority of biological nutrient removal research had concentrated on sewage i.e. blackwater and greywater combined, and not on its individual components. Thus, there is very little information on greywater and none was uncovered that looked at biological nutrient removal from greywater specifically. This study specifically focuses on greywater, a significant yet neglected waste stream in Trinidad and the wider Caribbean. Greywate-blackwater separation is widely practiced in the Caribbean and little or no treatment is given to greywater prior to its disposal to storm water drains or other receiving water bodies.

The aim of this work was to study nitrogen removal, primarily TN, from greywater by non-anaerobic biological processes and without the addition of external carbon. Nitrogen removal from synthetic wastewater has already been studied extensively (Yang and Zhang, 1995; Ouyang et al. 1998; Oh and Silverstein 1999; Mekenon et at., 2001; Moosavi et al., 2005). This work is unique in that it focused on the biological treatment of greywater generated from actual food preparation and laundering activities under bulk phase aerobic/anoxic carbon limiting conditions. The composition of the greywater is highly variable and is typically low strength.

## 2. Literature Review

### *2.1 The Sequencing Batch Reactor*

The Sequencing Batch Reactor (SBR) is very similar to the widely used activated sludge process. The main difference is that the five-step treatment cycle is carried out in one tank (Tchobanoglous and Burton, 1991). This provides great flexibility with evident design, process and operation advantages (Abreu and Estrada, n.d.). Any unit process operation or sequence can be altered after start up by simply changing the time allotments to effect increase, decrease, or restructuring of any part of the process while maintaining a physically simple system.

The stages of the process are: (1) Fill; (2) React; (3) Settle; (4) Decant and (5) Idle. Reactions that are initiated as the influent enters the reactor (Fill) are completed during 'React' with no flow entering or leaving the system. Solids separation occurs during the 'Settle' period. The effluent minus the solids is removed during 'Decanting'.

The 'Idle' period is the time that transpires between the end of one cycle and the beginning of the next. The 'Fill' phase may be static, mixed or aerated depending on the effluent quality requirements. Filling the reactor under static conditions results in a minimal reduction in substrate concentration during this phase as the energy input is negligible (Tchobanoglous and Burton, 1991).

### *2.2 Nitrogen Removal*

The main process for the removal of nitrogen is nitrification/denitrification (Prakasam and Loehr 1972). The nitrifiers can utilise ammonium as the electron acceptor instead of organic matter. As they also use inorganic carbon dioxide as the carbon source they are classified as autotrophic, i.e. they do not require organic matter to live, as do the heterotrophic organisms. Ammonium is oxidises to nitrate via the nitrite intermediate. Bacteria of the Nitrosomonous genus are responsible for the first stage of the reaction. The second stage is carried out using Nitrobacter oxidising bacteria. Nitrifying bacteria are slow growing and function best at temperatures above 25$^{o}$C. Mudrack and Kunst (1986) have suggested 7.2-8.0 as the optimum nitrification pH range. In order to achieve an extended degree of nitrification, it is necessary that the sludge age should be two to three times the generation time of nitrifiers, as only then are they able to accumulate in the biomass to an extent where their numbers balance the available supply of nitrogen (Qasim, 1999).

In contrast to the oxidation of reduced nitrogen compounds during nitrification, the process of denitrification involves a reduction of oxidised nitrogen compounds to elementary nitrogen (see Figure 1). Conventional theory holds that these two processes are mutually exclusive as they require opposing oxygen environments (Mudrack and Kunst, 1986; Tchobanoglous and Burton, 1991). Thus, they are spatially separated in conventional systems.

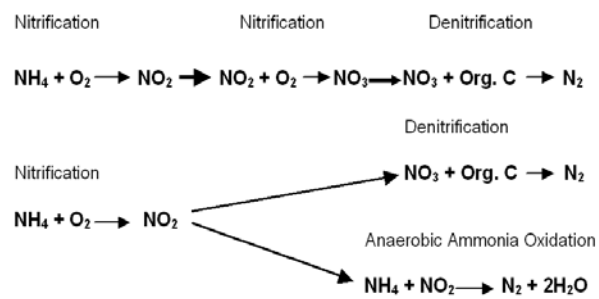



**Figure 1.** The Theory of Biological Nitrogen Removal
Source: Based on Rosenwikel et al. (2009)

During denitrification the nitrate ion functions as a terminal electron acceptor for the denitrifiers instead of atmospheric oxygen (Tchobanoglous and Burton, 1991).

Generally, current advanced biological nitrogen removal technologies may be categorised in one of two ways. Some technologies support nitrogen removal in the main stream by enhancing the nitrification efficiency in reaction tanks with augmented nitrifiers from return sludge, the other group uses partial nitrification or deammoniafication to remove nitrogen in partstreams (Rosenwinkel et al., 2009).

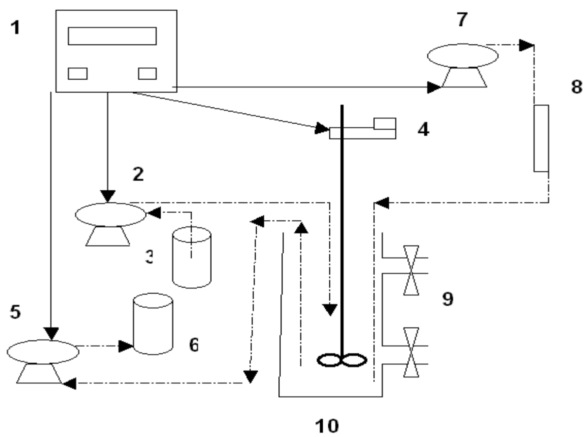
## 3. Materials and Methods

### *3.1 Sludge and Wastewater*

The seed for the reactor systems was obtained from a local municipal wastewater treatment plant. Raw greywater was collected from the Eric Williams Medical Sciences Complex, St. Augustine, Trinidad, stored in a chiller at 4$^{\circ}$C for no more than two days and removed as necessary to feed the reactor. The SBR was fed, at different times, composite greywater samples collected in the morning (A.M.) and afternoon (P.M.). The seed was acclimated.

### 3.2 The Sequencing Batch Reactor

A 10-L bench scale SBR, with an operating volume of 8 L, was fabricated and used (Fig. 2) in this experiment. It was equipped with five inlet/outlet ports for manual sampling and operated in the sequence of fill (10 min.), mix and aerate (5 hrs.), settle (40 mins.), and decant (10 mins.) phases. The solid retention times (SRTs) were 5, 7, 11 days and the ratio of feed introduced to reactor contents was 50% (Atherley-Ikechi, 2006).




*Keys:* 1: Time Controller
2: Influent Peristaltic Pump
3: Influent Holding Tank
4: Stirrer
5: Effluent Peristaltic Pump
6: Effluent Holding Tank
7: Air Pump
8: Rotometer and Dissolved Oxygen Meter
9: Manual Outlet/Wasting Valves
10: SBR

**Figure 2.** Schematic Diagram of the Set up of the SBR

### 3.3 Microbiological Study

Bacterial investigations were undertaken to investigate the occurrence of nitrifiers and denitrifiers in the SBR sludge. For nitrifier determination, Ammonium and Nitrite media were used (Benson, 1990). Nitrate Agar and Fluorescence Denitrification Medium (FN medium) were set up to test for nitrate reduction (Difco Laboratories, 1953).

### 3.4 Analytical Methods

Total Nitrogen (TN), chemical oxygen demand (COD) and carbonaceous biochemical oxygen demand ($CBOD_5^{25}$) were analysed according to APHA (1995) Standard Methods for the Examination of Water and Wastewater. Note that a nitrification inhibitor (HACH Nitrification Inhibitor, Formula 2533 (TM) – active ingredient 2-cholro-6 trichloromethylpyridine (N-Serve)) and an elevated temperature of 25$^o$C were used in the determination of biodegradable organic carbon. Ambient temperature is typically above 20$^o$C in the Caribbean. Accurate reflection of what occurs in nature, in a tropical environment, required the use of a higher temperature. Temperature, pH and dissolved oxygen (DO) were also measured.

## 4. Results and Discussions

### 4.1 Influent Wastewater Composition

System design is based on influent wastewater composition and as such the two are invariably linked to system performance.

Greywater samples collected in the morning (A.M.) exhibited TN in the range of 1.0-35.7 mg/L while afternoon (P.M.) samples reflected ranges of 4.4-43.6 mg/L TN. Influent TN concentration averaged 11.6 mg/L amongst the A.M. samples and 10.0 mg/L amongst the P.M. samples.

Total organic content, measured as COD, fluctuated between 36.0-645.0 mg/L for A.M. samples and 85.0-398.0 mg/L for P.M. samples. The biodegradable fraction, measured as $CBOD_5^{25}$, reflected values in the range 25.0-324.0 mg/L and 10.0-154.0 mg/L, respectively.

It is clear from the wide range of values obtained for the various parameters analysed, that greywater is highly variable and that its composition is highly dependent upon the habits of its producers. Comparison of the mean influent greywater parameter values with those given as typical for raw domestic wastewater by other researchers suggests that the raw greywater used was low strength (see Table 1).

Table 2 shows the mean influent parameter values. Temperature, pH and DO measurements were taken manually once/day during the settle phase. They were in the ranges of 19$^o$C-27$^o$C, 6.4-7.5 and 1.30-5.89 mg/L DO, respectively.

**Table 1.** Comparison of Greywater and Domestic Wastewater Composition

| Sources | Mean COD (mg/L) | Mean BOD5 (mg/L) | Mean TN (mg/L) |
|---|---|---|---|
| Jappersen and Solly (1994) | - | 160.0 | 17.6 |
| Bahadoorsingh (1998) | 451.0 | - | 5.3 as $NH_3$-N |
| Veneman and Stewart (2002) | - | 128.9 | 13.4 |
| Present Study (Atherley-Ikechi, 2006) | 248.2 | 93.8 as $CBOD_5^{25}$ | 10.8 |

**Table 2.** Summary of Mean SBR Influent Parameters used in the Various Treatments

| Treatment | Parameters | | | Ratios | |
|---|---|---|---|---|---|
| | COD | $CBOD_5^{25}$ | TN | COD: $CBOD_5^{25}$ | $CBOD_5^{25}$: TN |
| **5d SRT, A. M.** | **285.7** | 170.3 | 21.5 | 1.7 | 7.9 |
| **5d SRT, P.M.** | 274.0 | 101.3 | 6.7 | 2.7 | 15.0 |
| **7d SRT, A.M.** | 234.1 | 98.2 | 5.4 | 2.4 | 18.2 |
| **7d SRT, P.M.** | 283.9 | 59.9 | 16.7 | 4.7 | 3.6 |
| **11d SRT, A.M.** | 169.0 | 95.6 | 7.9 | 1.8 | 12.2 |
| **11d SRT, P.M.** | 242.7 | 37.3 | 6.5 | 6.5 | 5.7 |

*Note:* A.M. = Morning Greywater Sample; P.M. = Afternoon Greywater Sample

Microbiological studies revealed the presence of nitrifiers and aerobic denitrifying Pseudomonads, indicating that the facilitation of aerobic nitrogen reduction, from a microbial standpoint, was possible (Atherley-Ikechi, 2006).

### *4.2 SBR Performance*

Analysis of variance of average percentage COD removal revealed that neither varying SRT nor collection time (CT) independently combined, impacted removal rates significantly. Contrary to this, $CBOD_5^{25}$ recorded a P-value of 0.000, at the 5% α level, for CT indicating that varying this factor significantly influenced removal. Better percentage removals were obtained with the afternoon (94%) greywater samples than those collected in the morning (77%). The difference in the $CBOD_5^{25}$ removal between morning and afternoon samples is likely to be due to the composition of the influent greywater.

Considering that the morning samples (2.5 Kitchen: 1 Laundry) had a higher proportion of kitchen wastewater than the afternoon samples (1 Kitchen: 1 Laundry), it is likely that inhibitory substances were present in the morning samples at higher concentrations and therefore more significantly impacted bacterial degradation / utilisation in the morning samples leading to reduced $CBOD_5^{25}$ removal. The 1:1 ratio of afternoon samples also offered greater dilution of the inhibitors. Kitchen wastewater typically contains detergents and other antibacterial cleaning agents at higher concentrations than those found in laundry wastewater, particularly when the rinse water is considered (Western Australia, 2002). There was no significant difference between the two-way interactions however; removal was best at 7 d SRT × P.M. (97%).

From the COD: $CBOD_5^{25}$ ratios given in Table 2, it is apparent that the afternoon samples, on average, contained less readily biodegradable organic matter than the morning samples. Due to competition for limited resources, reduction of $CBOD_5^{25}$, under similar conditions, is expected to be greater where less of the resource exists. Another factor, which might have contributed to the lower levels of $CBOD_5^{25}$ reduction amongst the morning samples, is the presence of toxins. The elevated detergent and cleaning products load associated with the kitchen greywater of the morning samples is likely to have reduced the effective biodegradability of these samples. The difference in the contribution of kitchen greywater to the total greywater volume for morning samples (2.5 kitchen: 1 laundry) and afternoon samples (1 kitchen: 1 laundry) is believed to be an important factor.

TN was afforded better removal at 5 d SRT × A.M. (83%) and 7 d SRT × P.M. (83%) (see Figures 3 and 4).

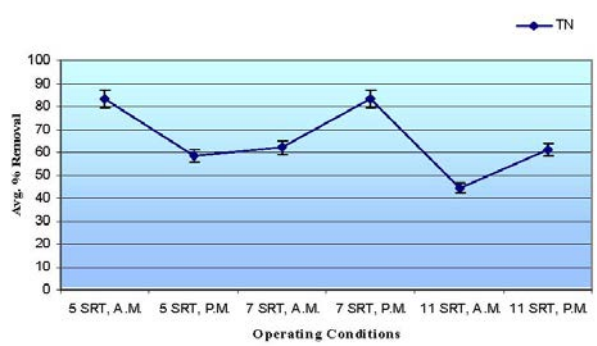



**Figure 3.** A Comparison of the Average Percentage Removal of TN from the SBR under Varying Operating Conditions

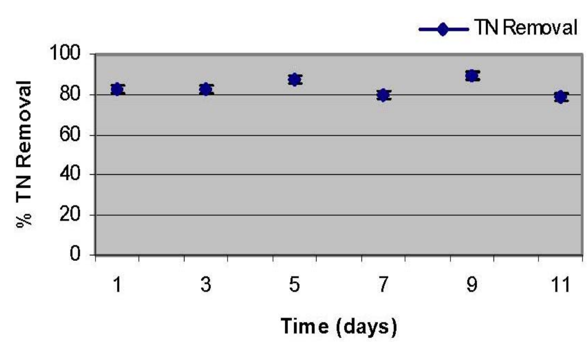



**Figure 4.** TN Removal when Operated under Optimal Conditions, 5 d SRT and A.M. Greywater

This better removal can be largely explained using the mean influent $CBOD_5^{25}$: TN ratios. As indicated by

Qasim (1999) nitrification, which precedes and supplies the raw material (nitrate) for denitrification, it is inhibited as BOD: TKN ($CBOD_5^{25}$: TN) ratios increase, particularly beyond 5. Analysis of the effect of SRT alone on TN removal showed comparable mean percentage removals at 5 d and 7 d SRT (i.e., 71% and 73%, respectively). A mean percentage removal of only 53% was attained when the SBR was operated at 11 d SRT. Collection time appeared to be less important to TN removal (i.e., P = 0.343, 64% mean TN removal - A.M. and 68% mean TN removal - P.M.).

## 5. Conclusions

Using low strength greywater generated from the laundry and restaurant of the Eric Williams Medical Sciences Complex in St. Augustine, Trinidad, the effects of solid retention time, hydraulic retention time, collection time, and the absence of an anaerobic phase on biological nutrient removal were examined. The high COD: $CBOD_5^{25}$ ratios observed, implied that the greywater was typically short chain volatile fatty acid (SCVFA) limiting. The SBR system is capable of removing 83% TN when conditions of 5 d SRT and A.M. samples are applied. It must be noted that the high levels of nitrogen removal achieved by the SBR were accomplished without the addition of external carbon, although the raw greywater was substrate-limiting, and without the presence of an anaerobic phase.

The SBR was able to deliver, consistently, effluent concentrations less than 5 mg/L TN. Attainment of such a low TN effluent concentration is significant as the Trinidad and Tobago Bureau of Standards' maximum permissible limit is 10 mg/L NH3-N to inland surface waters, coastal near-shore, and marine offshore for industrial effluents (Trinidad and Tobago, 1998). Permissible levels of nutrients are not specified in the domestic liquid effluent guidelines (Trinidad and Tobago, 1993). Effluent generated from the system was expected to have very low NH3-N concentrations as the latter constitutes only one component of TN.

The dissolved oxygen environment was monitored closely and fluctuated between anoxic and aerobic during the process of each cycle. This provided the opportunity for substantial nitrogen removal to take place.

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Hamid Farabi *was the Director of the Centre for Environmental Studies at The University of the West Indies, Trinidad. He possesses specialized knowledge in environmental engineering and management, toxic and hazardous waste, and health and safety issues in the Caribbean and Latin America. With 31 years experience, Dr. Farabi has a thorough understanding of the special problems and requirements of the region.*

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