Treatment of seawater salinity sewage with intermittent sand bioreactors

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ABSTRACT

In water stressed areas, flush toilets using fresh water are unsustainable. This paper explores the ability of intermittent sand bioreactors (ISBs) to treat seawater salinity septic tank effluent for on-site wastewater treatment in coastal regions. Two ISB designs, sand only and layered sand and gravel, are compared for treatment efficacy. Six columns of each design were constructed in the laboratory and dosed four times per day, for a total hydraulic loading rate of 4 cm/day, with artificial seawater salinity septic tank effluent over 21 months. Average TOC and ammonia removal for both designs averaged >90% and >96%, respectively. No statistically significant difference existed in the percent removal or effluent concentrations between the two designs. Half of the columns of each design produced effluent with >4 mg/L ammonia at least once during the study, resulting in discontinuation of wastewater application for seven weeks. This resting approach resulted in effective treatment for up to 9 months (limited by the end of the study). The results indicate that both ISB designs can treat artificial seawater salinity septic tank effluent, but that an additional 1/3 capacity is needed to maintain a consistent hydraulic loading rate while accounting for resting ISBs when treatment efficacy declines.

Key words: ammonia, clogging, intermittent sand bioreactor, on-site wastewater treatment, resting, seawater salinity sewage

HIGHLIGHTS

• Intermittent sand bioreactors (ISBs) effectively treated seawater salinity septic tank effluent.
• One- and three-layer ISBs performed similarly treating seawater salinity septic tank effluent.
• Effluent ammonia-N exceeded 4 mg/L at least once in 50% of columns of each ISB design.
• Seven weeks of resting restored ammonia removal capacity of ISBs.
• Recommend designing systems with 1/3 additional hydraulic loading rate capacity.
INTRODUCTION

People in areas with limited sanitation often desire flush toilets as a symbol of prosperity (Nawab et al. 2006; Morales et al. 2014; Mkhize et al. 2017). From a water resource perspective, flush toilets are deemed unsustainable. Water stress in many regions is seen as a barrier to ensuring availability and sustainable management of water and sanitation for all, the stated objective of Sustainable Development Goal 6 (U.N. 2020). Alternative designs for flush toilets that consider social acceptance by end-users, available water resources and development goals are needed. Considering about 40% of the world’s population lives within 60 miles of coastlines (U.N. 2017), flushing toilets with seawater is one potential solution. Hong Kong has utilized seawater flush toilets for over 50 years in nearly 80% of residencies (Li et al. 2005; Lockwood 2015).

To explore the potential for the use of seawater toilet flushing in rural, coastal contexts, the treatment of artificial seawater salinity septic tank effluent by intermittent sand bioreactors (ISBs) was studied. Intermittent sand bioreactors (ISBs) are on-site wastewater treatment systems designed for gravity flow of applied water through sand. The sand serves as a medium for the growth of biofilms that metabolize pollutants within the wastewater. The ability of ISBs to treat domestic wastewater for organic carbon and ammonia has been well described (Magdoff et al. 1974; Pell & Nyberg 1989a, 1989b; Widrig et al. 1996; Dubey & Sahu 2014). Performance is typically measured in ability to remove or transform organic matter, suspended solids, nitrogen and phosphorus and to avoid ponding of influent wastewater above the sand. A full-scale ISB was successfully operated for seven months treating septic tank effluent in a rural area of Brazil (Mattos de Oliveira Cruz et al. 2018).

Current ISB research focuses on design optimization. The impacts of media type, size and depth on treatment efficacy and clogging are main considerations. A comparison of one-layer and three-layer ISBs treating secondary effluent from a woodchip filter treating dairy-soiled water showed similar ammonia removal but significantly different COD removal between the two designs (Ruane et al. 2014). A fine sand system showed greater removal of COD and ammonia than coarse sand at the same depth, both treating septic tank effluent (Wang et al. 2019). Yet, fine sand filters have also been found to clog more...
quickly than coarse sand systems of the same depth when treating domestic greywater (Ochoa et al. 2015). Stratified, three-layer ISBs have been shown in the lab to treat turkey processing wastewater with up to 13 g/L NaCl effectively for COD and ammonia (Conroy et al. 2020).

This research studied the ability of one- and three-layer ISBs to treat artificial septic tank effluent with 35 g/L NaCl to understand if ISBs are a feasible candidate for rural, coastal sanitation systems. The objectives of this research were to: (1) Evaluate the ability of intermittent sand bioreactor (ISB) columns to treat seawater salinity septic tank effluent, and (2) Compare the ability of one- and three-layered ISB columns to treat seawater salinity septic tank effluent.

**METHODS**

**Influent production**

To produce artificial septic tank effluent, two lab-scale septic tanks were constructed using 190 L cylindrical drums. The tanks were initially filled with 189 L of tap water. Three times per week, 2.5 L of sludge and 11.4 L of 41 g NaCl/L salt water were added manually to each septic tank. The sludge was collected from the primary settling tank of the local municipal wastewater treatment plant (Southerly Wastewater Treatment Plant, Columbus, OH, USA) and refrigerated at 4 °C until use. To produce the salt water, a 190 L tank was filled with tap water and table salt to 41 g NaCl/L. This tank was constantly aerated using a Tetra Whisper pump (Spectrum Brand Inc, Blacksburg, VA, USA). The table salt consisted of NaCl with anticaking agent. The septic tank design was adapted from Peeples & Mancl (1998) to accommodate 190 L tanks. Effluent was drained from the septic tanks three times per week, at >24 hours after addition of sludge and salt water, and placed in 19 L buckets. This septic tank effluent acted as influent for the ISBs.

**Experimental design**

Twelve ISB columns were constructed in a laboratory setting. Six columns employed a three-layer design and six a one-layer design (Table 1). Both column designs incorporated 5 cm of gravel in the base as a preventative mechanism to retain the fine sand. A hole in the base of the columns allowed for effluent to drip into a 2 L container below.

Three of each ISB design were dosed with the artificial septic tank effluent using Masterflex peristaltic pumps (Cole Parmer, Vernon Hills, IL, USA) programmed to administer 175 mL doses on the surface of each sand column every six hours for a hydraulic loading rate of 40 L/m²/day. The study period was 21 months.

The term resting describes a seven-week period where no wastewater was dosed onto the columns. This maintenance method was initiated when the effluent ammonia exceeded 4 mg-N/L. This value was chosen to reflect an exceedance of the National Pollution Discharge Elimination System (NPDES) permit limits.

**Sampling**

ISB influent and effluent samples were collected monthly from months 4–21 for ammonia analysis. Conductivity, temperature, TOC, orthophosphate, nitrate/nitrite and pH were measured in influent and effluent samples for months 4–10, 13, 16 and 20. Turbidity was measured in months 5, 7–10, 16 and 20.

Influent values were determined by averaging duplicate samples from each of the two lab-scale septic tanks. Effluent samples were taken from each of the 12 ISBs, except when an ISB column was resting. The values were averaged for the ISBs of the same design to represent effluent values. Percent removal was calculated for each ISB in relation to the influent value for the septic tank associated with that ISB based on duplicate influent samples. The resulting percentages were then averaged for all ISBs of the same design. Data were not collected from resting ISB columns because no effluent was produced. Percent removal was calculated for TOC, ammonia, orthophosphate, and turbidity.

**Table 1** Details of the three-layer and one-layer intermittent sand bioreactor (ISB) designs utilized

| Sand type | Effective size (mm) | Uniformity coefficient | Three-layer depth (cm) | One-layer depth (cm) |
|-----------|---------------------|------------------------|------------------------|---------------------|
| Fine      | 0.30                | 2.8                    | 46                     | 76                  |
| Coarse    | 0.75                | 4.1                    | 15                     | –                   |
| Gravel    | 4.00                | 1                      | 15                     | –                   |
Analysis
Nitrate/Nitrite-nitrogen was analyzed using EPA Method 353.2/ Standard Method 4500 NO₃⁻ (O'Dell, 1993) with a method detection limit of 0.05 mg/L. TOC was analyzed using Standard Method for the Examination of Water and Wastewater 5310 B (APHA 2017) with a method detection limit of 5.0 mg/L. Ammonia-nitrogen was tested using HACH Method 8155, with a 0.02 mg/L uncertainty per reading (HACH Company, Loveland, CO, USA). Orthophosphate was tested using HACH Method 8048 with a sensitivity of 0.02 mg/L (HACH Company, Loveland, CO, USA). pH was analyzed using a YSI Pro 1020 (YSI Incorporated, Yellow Springs, OH, USA). Conductivity and temperature were measured using the Oakton CON 450 (Oakton Instruments, Vernon Hill, IL, USA). Turbidity was measured using the 2100Q portable turbidimeter (HACH Company, Loveland, CO, USA).

Statistics
F-tests were run to test for normal distribution using Microsoft Excel (2010). Based on the variance, a T-test or Mann-Whitney was utilized to compare the effluent values and percent removal between the ISB designs. Statistical significance was determined using an alpha of 0.05.

Resting scenarios
Bioreactor clogging (ponding on top) or producing effluent with ammonia that exceeds discharge limits can be remediated through resting the ISB. Additional capacity would be needed to allow for resting periods (Kang et al. 2007; Conroy et al. 2020). If additional capacity is built in, the resulting ammonia removal rates for the entire system could be maintained at a higher rate.

If additional capacity was not designed into the system, the increased ammonia effluent values may not be addressed because either (a) the bioreactors would need to continue to be dosed at the design loading without resting or (b) the effected ISBs could be rested but the loading rate would need to be increased on the remaining functional columns.

To compare these scenarios, the ammonia data was analyzed in two ways; (1) Extra Capacity: the missing values for percent ammonia removal from the rested columns are ignored based on the assumption that extra capacity allows these columns to be taken off-line without impacting the overall hydraulic loading rate and (2) No Extra Capacity: the missing values for percent ammonia removal from the rested columns are considered as 0% removal with the assumption that these ISB columns would eventually become non-viable without rest. The second scenario shows the lower limits of functionality for this system.

RESULTS AND DISCUSSION

Treatment efficacy
The TOC removal remained at 80% or above throughout months 4–20 of the study (Figure 1). The influent TOC was 113 ± 61 mg/L. Effluent TOC values for both sand bioreactor designs stayed below 10 mg/L throughout the study.

The ammonia removal from months 4–21 of operation remained greater than 75% (Figure 2). The influent ammonia ranged from 14–63 mg/L throughout the study, with an average of 32 mg/L. The effluent ammonia average of the one-layer sand bioreactor design never exceeded 4 mg/L. The effluent ammonia average of the three-layer design effluent exceeded 4 mg/L only once during the study (Figure 3).

The results of this study indicate that ISBs can treat septic tank effluent with seawater level salinity (as NaCl) to a similar extent as typical septic tank effluent. ISBs treating synthetic septic tank effluent at 2.6 times the hydraulic loading rate (HLR) of the current study achieved >80% average COD removal (Rodgers et al. 2011) and >90% BOD₅ (Sodamade et al. 2014). These systems had nearly complete nitrification of influent ammonia (Rodgers et al. 2011) and >98% ammonia removal (Sodamade et al. 2014). Wang et al. (2019) found that a sand filter removed 96% of COD and 98% of ammonia from septic tank effluent at three times the loading rate of the current study. Widrig et al. (1996) found nearly complete nitrification and BOD effluent values below discharge limits when operating ISBs treating artificial septic tank effluent with a loading rate six times that used in the current study. These percent removal of organic matter and ammonia in the literature on septic tank effluent without salt are similar to the results found in this study. This indicates that seawater salinity septic tank effluent can be treated efficiently by ISBs, but further exploration would be needed to compare loading rates.
Figure 1 | Total Organic Carbon (TOC) values for influent and effluent from one-layer and three-layer intermittent sand bioreactor (ISB) designs and the associated percent TOC removal while treating artificial seawater salinity septic tank effluent during 20 months of operation.

Figure 2 | Ammonia values for influent and effluent from one-layer and three-layer intermittent sand bioreactor (ISB) designs and the associated percent ammonia removal while treating artificial seawater salinity septic tank effluent during 21 months of operation.
Impact of ISB design on effluent quality and treatment efficacy

There was no statistically significant difference in TOC, ammonia, orthophosphate, nitrate/nitrite, turbidity, pH, temperature, or conductivity of the effluent from the one-layer and three-layer columns (Table 2). There was no statistically significant difference between the one-layer and three-layer designs in percent removal of TOC, ammonia, orthophosphate, or turbidity (Table 2).

These results indicate that varying the sand particle size within the top 30 cm of the ISB made no significant difference in treatment efficacy of the current wastewater. This varies from the findings of Ruane et al. (2014) that stratified sand columns removed more COD than single layer columns when treating pre-treated dairy-soiled wastewater. A fine sand system showed greater removal of COD and ammonia than coarse sand at the same depth, both treating septic tank effluent (Wang et al. 2019). These conflicting results within the literature each showed variation between designs, whereas the current study indicates both the proposed three-layer and one-layer ISB designs can treat seawater salinity septic tank effluent. This lack of differences is important because this allows for design adjustments to local material availability and construction preferences.

Occurrence and frequency of ammonia limit exceedance and subsequent resting

Three of the three-layer columns and three of the one-layer columns did not produce effluent with greater than 4 mg/L NH₃-N throughout the entire 21 months of operation. Therefore, no resting was needed for these columns.

One or more exceedances of the 4 mg/L ammonia limit occurred in three of the three-layer ISB columns and three of the one-layer ISB columns. The months of operation prior to exceedance varied from 10–14 months (Table 3). A second exceedance of the ammonia limit occurred in two of the three-layer ISB columns and one of the one-layer ISB columns (Table 3).

Table 2 | Effluent values and percent removal for various parameters

| Parameter            | Influent       | Effluent   | Percent removal (%) | Percent removal (%) |
|----------------------|---------------|------------|---------------------|---------------------|
| TOC (mg/L)           | 112.6 ± 60.5  | 6.7 ± 1.5  | 5.9 ± 0.9           | 91.5 ± 5.6          | 93.5 ± 3.1          |
| NH₃-N (mg/L)         | 31.2 ± 12.2   | 0.9 ± 1.6  | 0.3 ± 0.5           | 96.3 ± 7.0          | 99.0 ± 1.5          |
| PO₄³⁻ (mg/L)         | 29.0 ± 11.5   | 22.3 ± 5.2 | 21.4 ± 6.2          | 16.1 ± 23.9         | 18.6 ± 24.9         |
| NO₃⁻/NO₂⁻N (mg/L)   | 0.1 ± 0.0     | 38.9 ± 13.9| 43.3 ± 16.8         | –                   | –                   |
| Turbidity (NTU)      | 49.4 ± 30.0   | 3.0 ± 2.3  | 2.1 ± 1.3           | 92.4 ± 6.3          | 94.6 ± 3.9          |
| pH                   | 6.6 ± 0.2     | 8.1 ± 0.2  | 8.1 ± 0.1           | –                   | –                   |
| Temperature (°C)     | 20.9 ± 1.8    | 19.3 ± 1.4 | 19.6 ± 1.3          | –                   | –                   |
| Conductivity (mS/cm) | 56.0 ± 2.3    | 61.7 ± 2.5 | 62.2 ± 2.7          | –                   | –                   |

No statistically significant difference between three-layer and one-layer design effluent or percent removal was found.
Resting was implemented when the ammonia value exceeded 4 mg/L. This exceedance was typically preceded by water ponding on top of the fine sand layer of the ISB. Visible indicators of water backing up were observed at the top of the fine sand layer in the three-layer ISB columns and on the top of the one-layer ISB columns. Several studies indicate that in both stratified and single layer designs, the top layer is where most organic matter buildup is detected (Ruane et al. 2014; Ochoa et al. 2015; Wang et al. 2019). Organic matter buildup was noticed in the top 3 cm of both the stratified and single layer columns tested by Ruane et al. (2014). They found that the stratified columns had organic matter buildup deeper into the columns, with limited buildup seen in the single layer columns at 12 cm depth (Ruane et al. 2014). The coarse sand and gravel layers in the current study did not result in a flow boundary layer at the top of either of these layers and the two ISB designs varied in where visible ponding was observed. This indicates that the three-layer ISB may be a beneficial design because some level of clogging is expected. Increased hydraulic retention time can thus occur without water ponding at the ISB surface. Yet, the observed relationship between water ponding and reduced treatment may indicate the one-layer ISB is preferable because clogging is immediately visible at the top of the ISB.

### Implications of resting for design requirements

To explore the impacts designing additional ISB capacity into a system would have on treatment, by allowing for resting without reducing loading rate, observed values were compared with the calculated scenario of designing a system exactly to the anticipated hydraulic loading capacity. The calculated values in Figure 4 represent an assumption of 0% ammonia removal for the duration of the study for each column with an effluent value that exceeded 4 mg/L. Based on this assumption of

| Column type | Months from start of operation to first instance of ammonia effluent >4 mg-N/L | Months from start of operation to second instance of ammonia effluent >4 mg-N/L |
|-------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Three-layer | 10                                                                               | 14                                                                               |
| One-layer   | 10                                                                               | –                                                                                 |
| Three-layer | 11                                                                               | –                                                                                 |
| One-layer   | 11                                                                               | 17                                                                               |
| Three-layer | 14                                                                               | 20                                                                               |
| One-layer   | 14                                                                               | –                                                                                 |

– indicates the column did not exceed 4 mg/L NH₃-N for the remainder of the study.

Figure 4 | Ammonia removal showing values (observed) with resting columns excluded and values (calculated) assuming resting columns were continuously dosed and removed 0% ammonia.
designing no additional capacity for resting, the three-layer columns would have maintained 47% ammonia removal and the one-layer columns maintained 50% ammonia removal throughout the study. With the capacity for resting some of the sand bioreactors, the ammonia removal was >95% for the one-layer and >76% for the 3-layer columns.

These findings support resting as a simple and effective management strategy to regain functionality of the ISB. The effectiveness of this method has been observed in previous studies of ISB treating turkey processing wastewater both with (Conroy et al. 2020) and without (Kang et al. 2007) added salt. For each column design, the greatest number of columns resting at any given time was two of six (Table 3). This indicates that if resting is employed as a management strategy, an extra 1/3 capacity should be included in the system design. As shown in the modeled results (Figure 4), if resting capacity is not provided, the average treatment efficacy for ammonia removal could drop to 50% within 16 months.

CONCLUSIONS

The results of this research indicate that ISBs can treat domestic sewage with salinity values representative of seawater. Further exploration is needed to determine the range of possible loading rates that can be treated effectively. Due to effluent values exceeding ammonia discharge limits and ponding in some ISBs of each design, it is recommended that ISB systems treating seawater salinity septic tank effluent be designed with 1.3 times the capacity needed for the anticipated flow rate. Both the one-layer and three-layer designs showed similar treatment efficacy and resting requirements. This indicates that both designs are functional treatment options, broadening opportunities for ISB application in places where accessing sand of certain effective sizes could be difficult.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. Data available at https://zenodo.org/record/4818578#.YVX74JrMKUl

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