BIOLOGICAL TREATMENT AND REUSE OF HUMAN SPACE EXPLORATION WASTEWATER

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ABSTRACT

Extending a human presence in the solar system requires in-situ resource recycling. Entrapped Mixed Microbial Cell (EMMC) process may be considered an alternative to achieving this aim. The intent of this investigation is to develop an operational criteria, process performance and economic evaluation to meet NASA needs. A double-layer EMMC configuration bioreactor of 7L at a packing ratio of 17.1% operated at an HRT of 6 hours, continuous aeration (1-1.2L/L/day), temperature of 25°C ±2 was tested. The organic loading rate fluctuated 1.0-4.5 mg/L/day. The EMMC process performance reached a steady state ~20 days. It demonstrated discharge efficacy of TCOD >94%, SCOD >97% removal, no solids generated, and an average nitrogen removal of 35.9%. Simultaneous removal organics and nitrogen may be attributed to the long sludge retention times that EMMC achieves because it allows for slow growing bacteria such as nitrifiers to thrive. It would cost $0.08 to treat 10 gallons of wastewater a day (twice as much as water needed to treat). The EMMC reactor design depending on the design can treat 60% to 100% of daily wastewater within one day. It also requires considerably less space compared to physiochemical treatment processes and if integrated with other systems may be capable to renovate water to levels permissible for human consumption.

INTRODUCTION

In situ resource reutilization is necessary for long-term manned mission to be possible. Current physiochemical treatment processes (PTP) of space wastewater rely upon a combination of physical and chemical methods to treat wastewater (Curie and Morcone, 2008). However, disadvantages of incorporating PTPs include large unit-space requirements, significant energy usage, complex operation/maintenance, and the use of chemicals and machinery to achieve treatment/renovation objectives. Biological treatment processes, on the other hand, use microorganisms to metabolize, treat, and even renovate the wastewater to a reusable form.

Entrapped mixed microbial cell (EMMC) may be considered an alternative biological treatment method for in-situ resource reutilization of space wastewater. Extensive research on EMMC in treating domestic and agriculture wastewater have been realized as well as using the system to possibly treat wastewater streams for potable drinking water applications while requiring small spatial area. Consequently, EMMC seems to be a feasible candidate for resource recovery and reutilization for the human space exploration needs (Yang et al., 1988; Yang et al., 1994; Yang et al., 1997; Yang et al., 2002; Yang et al., 2003; Yang et al., 2005; Yang, 2007). The purpose of this investigation is to develop operational conditions and design criteria of the EMMC process to treat the human space exploration wastewater.
METHODS

EMMC Preparation

The EMMC carriers were prepared by modifying the carrier using a plastic bio-barrel as the “frame” (Yang & See, 1991). The carriers house the microorganism which metabolizes the pollutants. The mixed microbial cells used in this study were obtained from dewatered sludge in East Honolulu Wastewater Treatment Plant (EHWTP), Honolulu, Hawai‘i.

A mixture of 100 ml of 10% (w/v) cellulose triacetate using methane chloride as a solvent was mixed with dewatered sludge containing about 90% water. After mixing uniformly, the Biobarrel rings were added to be coated with the mixture of gel and microbial cells for carrier shaping. The well-coated bio-carriers were firmed in 100% toluene solution. The hardened carriers were washed with tap-water and then packed in the reactor for further experiments. The organic solvents (methane chloride and toluene) can be recovered by a combination of freezing and distillation methods (Zhang, 1995). Figure 1 depicts prepared EMMC carriers.

Design Criteria

The design must be appropriate in size that could be installed into the spacecraft based upon a crew exploration vehicle (CEV) occupying three to six persons within a very confined area. It has been estimated that during long-term human space mission an overall 12.680L of wastewater (hygienic + urine) would need to be treated daily. (Horneck et al, 2003; M. Czuppalla et al, 2004).

System Design and operation

A laboratory scale system of a double-layer configuration was setup as shown in Figure 2. The influent domestic wastewater is pumped from a tank by a peristaltic pump. The influent water pumped is synthetic wastewater (table 1). The water chemical composition mirrors Human Space exploration wastewater which is similar to domestic wastewater of weak strength (table 2). The flow is controlled by digital liquid flow meter. The wastewater enters the bioreactor containing two layers of EMMC—figure 1. Each layer is packed with carriers that have mixtures of activated microorganisms attached to it. A 17.1% carrier packing ratio fills the bioreactor. These microorganisms together degrade the constituents operating under steady-state conditions at a temperature of 25 ± 2°C, and a continuous air flow rate of 1~1.2 L/L void volume/min. The water remains in the bioreactor for a hydraulic retention time (HRT) of 6 hours. After that period of time, the degraded water flows out into the effluent tank. The current design size can meet 60% to 100% of the crew wastewater treatment needs depending on operation.

Feed characteristics

Synthetic wastewater was prepared in stock solution using sucrose as a carbon source. The SCOD and NH₄⁺-N concentrations of the synthetic feed incorporated in this study ranged from 100-1,100 mg/L and ##-## mg/L, respectively. The synthetic wastewater composition mirrors domestic wastewater characteristics; table 1 presents the synthetic wastewater composition.
Analytical methods

Influent and effluent samples were collected every 48 hours. The samples were analyzed for total chemical oxygen demand (TCOD), soluble chemical oxygen demand (SCOD), ammonia nitrogen (NH\(_3\)-N), nitrite nitrogen (NO\(_2\)-N), nitrate nitrogen (NO\(_3\)-N), total suspended solids (TSS), and pH. All the results present the mean of at least 7 experiment data collected under steady state conditions.

RESULTS

Operation criteria

The process performance of the system was assessed by the hydraulic retention time (HRT) which refers to the amount of time the liquid flows through the bioreactor. Previous studies determined that the optimal HRT to operate the double layer system is at 6 hours. The double-layer design was selected also to be the optimal configuration to yield high carbon and nitrogen removal. The system was operated at an HRT 6 hours under continuous aeration supply at 1-1.2 L/L/day.

Process performance

Nutrients of major concern in wastewater are carbon and nitrogen. Excess levels in waters can lead to environmental hypoxia, odor problems, septic conditions, and if consumed causes poisoning, illness or severe cases, even death (WHO, 2009). pH, Total chemical oxygen demand (TCOD) and soluble chemical oxygen demand (SCOD), ammonia nitrogen, and Total Suspended Solids (TSS) were monitored; figures 3, 4, 5, and table 2, respectively. The process performance was also evaluated on COD removal efficiency as shown in figure 6.

DISCUSSION

Operation criteria and process performance

Previous studies determined that increased mass transfer efficiencies could be realized utilizing a double-layer EMMC configuration rather than a single-layer. This could be a result of reactors in series contained. A double-layer configuration operating at an HRT of 6 hours and continuous aeration schedule performance was determined as shown in Figures 3, 4, 5, and 6. The system reached a steady state in about twenty days. The total chemical oxygen demand, soluble chemical oxygen demand and ammonia nitrogen removal efficiencies were 94.5%, 97.6%, and 35.9%, respectively, at steady state. A major setback encountered during the study was controlling the influent concentration. The organic loading rate ranged from 1.0-4.5 mg/L/day. Despite the variable organic loading rate, the effluent TCOD and SCOD concentrations were shown to be consistently low.

The EMMC process is capable of effective simultaneous removal of carbon and nitrogen because it is capable of achieving high SRT (Solid Retention Time). This ensures a high biomass concentration is entrapped in the system which allows for slow growing bacteria such as nitrifiers. The systems low nitrogen removal could be attributed that the nitrifiers are still growing, as exhibited in the increased ammonia nitrogen removal over time (Figure 6). It is recommended that more time is required to further evaluate the SRT effects in contributing to effective simultaneous removal of carbon and nitrogen.
Design/Operation criteria and economic evaluation

Based upon the above experimental results, design/operation criteria were developed and are presented in table 4. An economic analysis was calculated from these criteria for the operation of 10 gallons/day. The capital cost was estimated to be $4,046.25 which includes the cost of: EMMC carriers, the bioreactor, air supply and feeding pipes. The annual operation/maintenance cost ($14.60) is principally includes electricity. A useful life of 15 years was assumed (Yang et al, 1997). The Net Present Worth was assessed at $4,171.59. Consequently to treat 10 gallons of 6 man crew exploration per day is $0.08. The above cost analysis is an estimation based for operating the system on earth. The analysis would need to be further revised to include the special space cost considerations neglected in the calculations.

Potential application for long-term manned galactic missions

Short-duration manned or low Earth orbit missions depend on re-supply techniques of water and do not treat any generated wastewater; however, to extend a human presence it is imperative to develop technologies capable of treating and recycling wastewater streams efficiently and quickly. This inquiry is relevant to NASA objectives to identify and test life support systems by 2010 (NASA, pp. 14, 2006, Sub-goal 3.F.2).

Other treatment systems have been considered for this specific application such as wetlands, however, the large space required and complex operation/maintenance required may be infeasible for long-term space applications (Nelson et al, 2001; Nelson et al, 2003). Recently, the agency tested a wastewater recovery using PTP technologies in space. To recover drinkable water, two processes were used to treat (1) urine water and (2) other wastewater streams. The urine water was treated by distillation and the other wastewater streams used a series of chemical treatment and filter processes to produce drinkable water for human consumption (Curie and Morcone, 2008). The concept was successfully tested once after five days of attempt (Schneider, 2008).

EMMC has been demonstrated to remove organics and inorganics under land-limited conditions. It would be best to integrate the EMMC process with other processes, in particular membrane bioreactor (MBR as shown in Figure 8) in order to produce drinkable water for human consumption. The integration of the compact sized MBR proves advantageous because it yields low sludge production, good solid/liquid separation, and eliminates pathogens; though membrane fouling is one area of concern (Nueugjamnong, 2004). Further inquiry on coupling EMMC and MBR is needed to evaluate process performance and operational conditions. This could be explored when I enter at the Biological Engineering graduate degree program at the University of Hawai‘i at Mānoa in the Fall 2009.

CONCLUSION

Entrapped Mixed Microbial Cell (EMMC) was investigated to determine the utility of the biological treatment process to meet the needs of NASA to treat and reuse human space exploration wastewater streams. Currently, NASA depends upon re-supply to replenish water resources on the low Earth orbit and short-term manned missions. A process performance was evaluated for a double-layer EMMC configuration at an HRT of 6 hours, continuous aeration (1-
1.2 L/L/day), temperature of 25°C ±2, 17.1% packing ratio. Efficacies of TCOD >94%, SCOD >97% removal and no solid discharge of effluent wastewaters were achieved. An economic analysis based on applications on earth determined that it would cost approximately $2.30 USD per month to treat 30 gallons of water. EMMC compared to other biological treatment processes (i.e. activated sludge process etc.) is capable of much longer sludge retention times (SRT) of >100 days, useful life of >10 years, and suffices land limited conditions. The operation and maintenance of the system is much simpler in contrast to complex physiochemical treatment process. The proposed system design could be integrated with other compact unit processes to provide in-situ water resource reutilization thereby satiating NASA’s thirst to achieve their ultimate quest to expand a human presence to the moon, the red planet, and beyond.

ACKNOWLEDGEMENTS

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REFERENCES


**APPENDIX**

*Figure 1. Prepared EMMC carrier*
Figure 2. Design 1: Double layer EMMC (reactor volume 7 L, 17.1% packing ratio, HRT 6 hrs)

Figure 3. pH results of study

Figure 4. Total Chemical Oxygen Demand
Figure 5. Soluble Chemical Oxygen Demand

Figure 6. Ammonia Nitrogen, 35.9% average removal efficiency
Figure 7. COD removal efficiency

Figure 8. Membrane Bioreactor Configuration (Nuengjamneng, 2004)
<table>
<thead>
<tr>
<th>Constituent</th>
<th>Concentration (mg/L)</th>
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<tbody>
<tr>
<td>Sucrose, C_{12}H_{22}O_{11}</td>
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</tr>
<tr>
<td>Ammonium sulfate, (NH_4)_2SO_4</td>
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</tr>
<tr>
<td>Monobasic potassium phosphate, KH_2PO_4*KH_2</td>
<td>260</td>
</tr>
<tr>
<td>Dibasic potassium phosphate, KH_2PO_4</td>
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<tr>
<td>Sodium Carbonate, Na_2CO_3</td>
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<tr>
<td>Calcium chloride, CaCl_2</td>
<td>20</td>
</tr>
<tr>
<td>Ferric chloride, FeCl_3·6H_2O</td>
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</tbody>
</table>

**Table 1.** Synthetic wastewater composition.

<table>
<thead>
<tr>
<th></th>
<th>Influent</th>
<th>Effluent</th>
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</thead>
<tbody>
<tr>
<td>SS (μg/L)</td>
<td>66.9± 45</td>
<td>32.7 ± 29</td>
</tr>
<tr>
<td>pH</td>
<td>7.22 ± 0.37</td>
<td>7.54 ± 0.53</td>
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**Table 2.** Suspended solids and pH influent and effluent quality