Electronic Supplementary Material (ESI) for Environmental Science-Water Research & Technology

Electronic Supplementary Information (ESI)

Thermal Swing Intermittently-Operated Biological Activated Carbon Filtration for Rapid, Non-Sewered Treatment of Psychrophilic Black Water

Andy Y. Hur[1,2], Martin A. Page[1,*], and Jeremy S. Guest[2]

[1] U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory; P.O. Box 9005, Champaign, IL 61826

[2] University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering; 205 N. Mathews Ave, Urbana, IL 61801

List of Tables

List of Figures

Section S1. Determination of Energy Consumption

S1.1 Aeration

$$P_w = \frac{wRT_1}{29.7ne}\left[\left(\frac{p_2}{p_1}\right)^{0.283} - 1\right]$$

(Equation S1)

where P_w is the power requirement (kW), w is the weight flow rate of air – volumetric flow rate of air, Q_a, times specific weight – ($kg \cdot s^{-1}$), R is the engineering gas constant for air (8.314 $kJ \cdot kmol^{-1} \cdot K^{-1}$, T_1 is the absolute inlet pressure (K), p_1 is the absolute inlet pressure (atm), p_2 is the absolute outlet pressure (atm), n is 0.283, and e is efficiency (0.80)[1].

S1.2 Pumping (influent, backwash)

The total dynamic head (TDH) is comprised of the static head (H_{ts}), the friction head (H_{sf}, H_{df}), and minor losses (H_m). For AnMBRs, permeate pumping must also be considered by including transmembrane pressure (TMP). TDH can then be calculated by the equation below:

$$TDH = H_{ts} + H_{sf} + H_{df} + H_m(+ TMP)$$

(Equation S2)

However, because minor losses are insignificant compared to the static and friction heads, H_m can be negated. Terms in the TDH equation are further elaborated below:

Total Static Head, H_{ts} (ft): The total static head of pumping can be calculated by the equation below.

$$H_{ts} = H_{ds} - H_{ss}$$

(Equation S3)

Suction Static Head, H_{ss} (ft): Suction static head of pumping is the elevation difference between the water level in the reactor and the centerline of the permeate pump.

Discharge Static Head, H_{ds} (ft): Discharge static head of pumping is the elevation difference between the centerline of the pump and the centerline of the effluent (where water is discharged). The effluent is assumed to be the highest point, thus setting the hydraulic reference.

Suction Friction Head, H_{sf} (ft): Suction friction head can be estimated using the Hazen-Williams equation. Suction friction head refers to the friction loss caused in the pipes on the suction side.

$$H_{sf} = 3.02LV^{1.85}C^{-1.85}D^{-1.17}$$

(Equation S4)

where L is the length of the pipe (ft), V is the velocity of the liquid in the pipe ($ft \cdot s^{-1}$), D is the inner diameter of the pipe (ft) and C is the Hazen-Williams coefficient (110).

Discharge Friction Head, Hdf (ft): Discharge friction head refers to the friction loss caused in the pipes on the discharge side. The Hazen-Williams equation is also used to calculate this value.

Transmembrane Pressure, TMP (ft): This refers to head loss through GAC media and this value is assumed to be 0.5ft.

Brake Horsepower, BHP: BHP is the amount of horsepower required to drive the pump and can be calculated by the equation below:

$$BHP = \frac{Q \cdot TDH}{3960 \cdot Pump\ Efficiency}$$

(Equation S5)

where Q is the flow rate (gpm), TDH is the total dynamic head (ft), and the pump efficiency is assumed to be 80%.

Energy consumption, E (kW): The amount of energy input into the motor of the pump can be calculated as:

$$E = \frac{0.746 \cdot BHP}{Motor\ Efficiency}$$

(Equation S6)

where BHP is the break horsepower (hp) and motor efficiency is assumed to be 70%.

S1.3 Heating

The heat requirement for the influent wastewater stream can be computed as follows[1]:

$$q = cdQ\Delta T$$

(Equation S7)

where q is the power requirement (kJ), c is the specific heat of the wastewater stream ($kJ \cdot kg^{-1} \cdot C^{-1}$), d is density of wastewater ($kg \cdot m^{-3}$), Q is daily volumetric loading (m^3), and ΔT is the temperature change (°C).

Also, the heat requirement for the GAC media bioregeneration can be computed as follows:

$$q = c_p m \Delta T e$$

(Equation S8)

where q is the power requirement (kJ), c_p is the specific heat of GAC ($kJ \cdot kg^{-1} \cdot C^{-1}$), m is mass of GAC in the filter (kg), ΔT is the temperature change (°C), and e is heat transfer efficiency (%).

S1.4 Mechanical Mixing

The mechanical mixing energy requirement for the anaerobic membrane bioreactor can be calculated as follows:

$$G = \sqrt{\frac{P}{\mu_w V_r}}$$

(Equation S9)

where G is the mixing intensity, μ_w is the viscosity of wastewater ($N \cdot s \cdot m^{-2}$), P is power (W), and V_r is volume of the reactor (m^3).

S1.4 Assumption for Energy Consumption Calculations

Table ESI-1. Assumptions associated with each of the energy-consuming processes listed above along with values and citations thereof.

Assumption	Value	Citation
General		
Influent flow rate	$4{,}542.5\ L \cdot d^{-1}$	-
EBCT	113 min	-
Influent COD	$1200\ mg \cdot L^{-1}$	-
Specific heat of wastewater (20°C)	$4.2\ kJ \cdot kg^{-1} \cdot °C^{-1}$	[1]
Density of wastewater (20°C)	$998.2063\ kg \cdot m^{-3}$	[2]
Pipe internal diameter	0.5 in	-
Aeration for Backwash		
Air backwash rate, 1st-air	$0.8\text{-}1.6\ m^3 \cdot m^2 \cdot min^{-1}$	[3]
Air backwash rate, 2nd-air + water	$0.8\text{-}1.6\ m^3 \cdot m^2 \cdot min^{-1}$	[3]
Temperature	23°C	-
Outlet pressure	1.4 atm	-
Efficiency	80%	[1]
Backwash Pumping		
Total static head	2 ft	-
Suction friction head length	15 ft	-
Discharge friction head length	15 ft	-
Water backwash rate, 2nd-air + water	$0.4\ m^3 \cdot m^2 \cdot min^{-1}$	[2]
Water backwash rate, 3rd-water	$0.75\ m^3 \cdot m^2 \cdot min^{-1}$	[2]
Velocity in pipes	$5\text{-}11\ ft \cdot s^{-1}$	-
Influent Pumping		
Total static head	5 ft	-
Suction friction head length	30 ft	-
Discharge friction head length	30 ft	-
Flow rate for BHP calculation	Influent	-
Velocity in pipes	$3\text{-}4\ ft \cdot s^{-1}$	-
Heating		
Influent temperature	10-23°C	-
Desired heating temperature	28°C or 35°C	-

GAC density	700 kg/m^3	
Specific heat of GAC	1.125 kJ·kg^{-1}·°C^{-1}	
Heat transfer efficiency	100%	
Mixing		
Mixing intensity, Stirred Tank	100-200 s-1	-

Section S2. Bench Scale Experiment Results

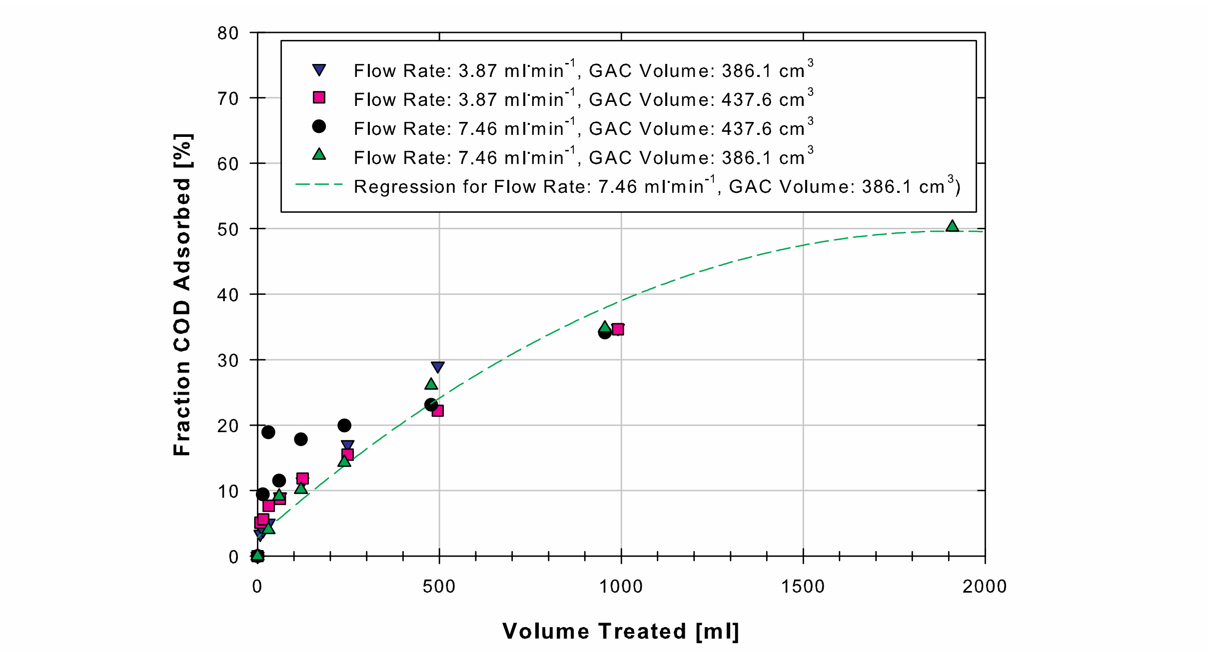

Figure ESI-1. Breakthrough experiments using clean, sterile GAC and synthetic high strength wastewater at varying flow rates and column bed depths (23°C).

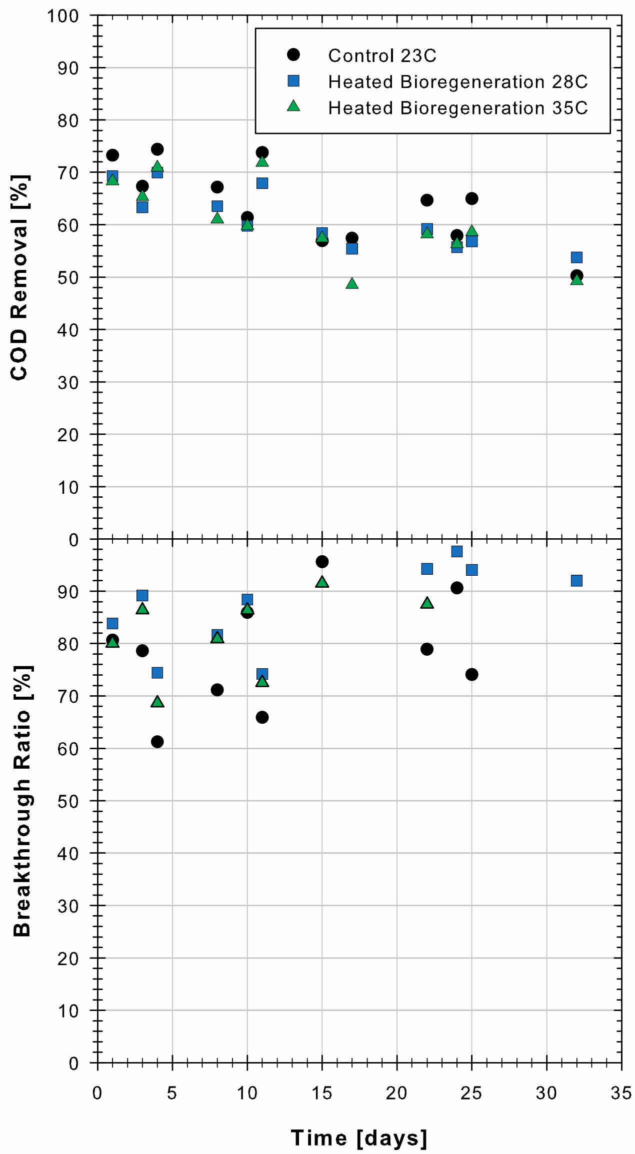

Figure ESI-2. Removal of organic contaminants measured in terms of COD % removal and breakthrough progression measured in terms of ratio (A_{180}/A_{270}), by IOBAC and TS-IOBAC at room ambient temperature (23°C). The average influent COD value during this test was 1266 ± 57 mg/L. A_{180} = Adsorption measured as COD % removal from 180- min effluent sample. A_{270} = Adsorption measured as COD % removal from 270-min effluent sample.

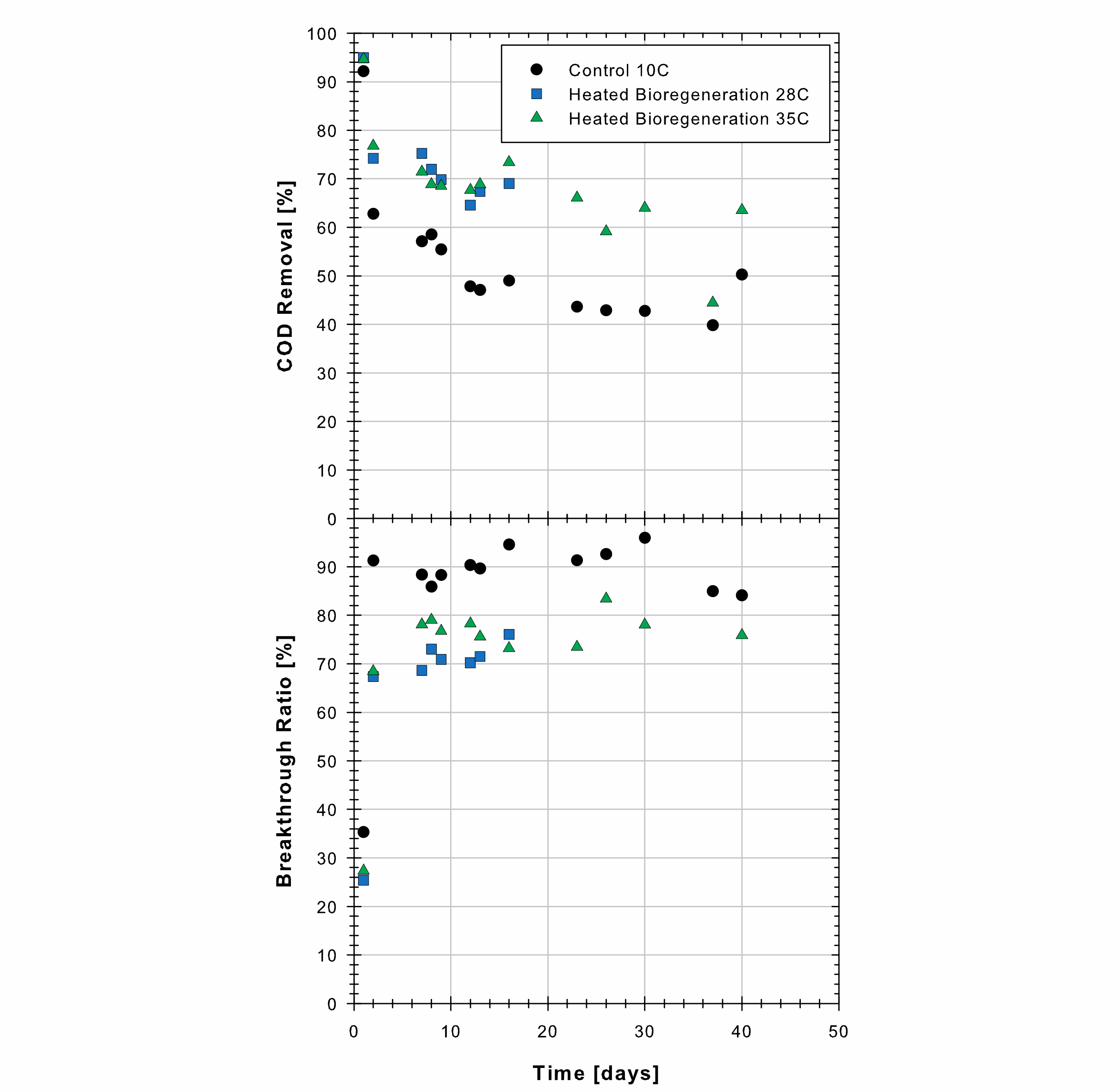

Figure ESI-3. Removal of organic contaminants measured in terms of COD % removal and breakthrough progression measured in terms of ratio (A_{180}/A_{270}), by IOBAC and TS-IOBAC at cool ambient temperature (10°C). Column 2 (bioregeneration temperature = 28°C) sample data missing due to broken valve during the last 2-week test period. The average influent COD value during this test was 1283 ± 39 mg/L. A_{180} = Adsorption measured as COD % removal from 180-min effluent sample. A_{270} = Adsorption measured as COD % removal from 270-min effluent sample.

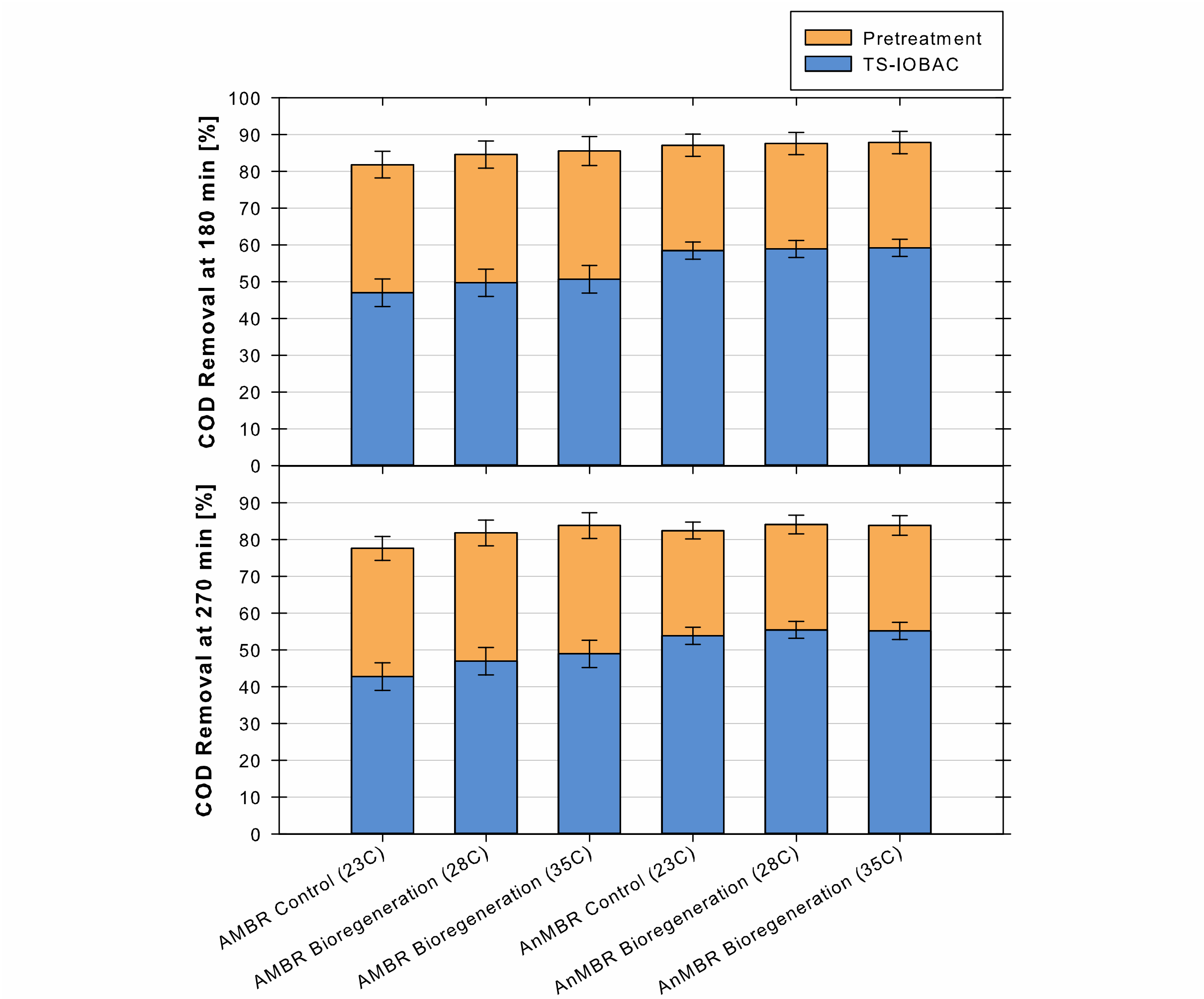

Figure ESI-4. Removal of organic contaminants as a result of aerobic bioreactor (AeMBR) and anaerobic membrane bioreactor (AnMBR) pretreatment flowed by IOBAC or TS-IOBAC at room ambient temperature (23°C). The average influent COD value during this test was 1249 ± 71 mg/L for AeMBR integration study and 1274 ± 24 mg/L for AnMBR integration study.

References

1. G. Tchobanoglous, F. L. Burton, and H. D. Stensel, Wastewater Engineering: Treatment and Reuse, McGraw-Hill Professional, 2003.
2. D. W. Hendricks, Fundamentals of water treatment unit processes: physical, chemical, and biological, CRC Press, Boca Raton, 2011.
3. Metcalf & Eddy 5th Edition, pg 1168-1169