Supporting Information

Aerobic fluidizing membrane bioreactor treating municipal wastewater with membrane fouling control by GAC souring

Yaoli Ye [a], Nicole Labarge [a], Hiroyuki Kashima [a], Kyoung-Yeol Kim [a], Peiying Hong [b], Pascal E. Saikaly [b], and Bruce E. Logan[a,*]

[a] Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA, 16802

[b] Biological and Environmental Sciences and Engineering Division, King Abdullah University of Science and Technology (KAUST), 4700 King Abdullah Boulevard, Thuwal 23955-6900, Saudi Arabia

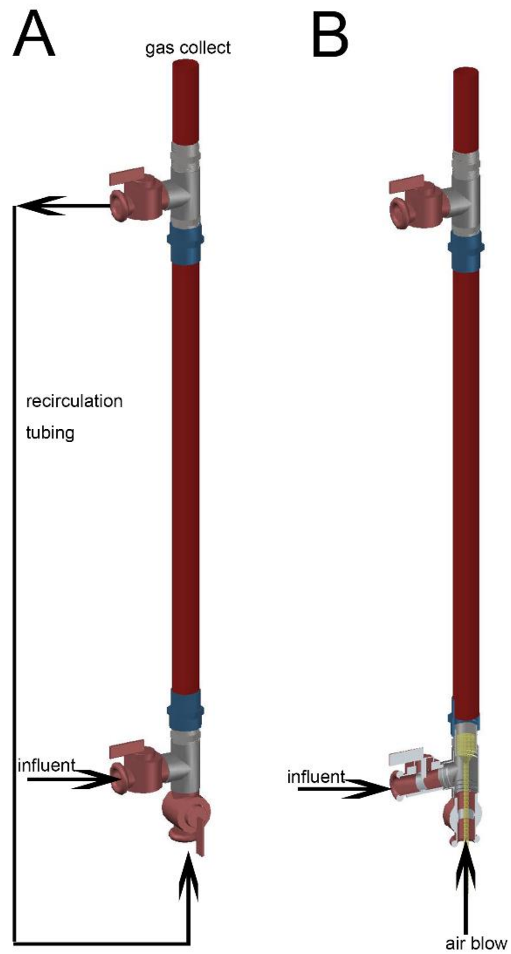

Fig. S1 – Reactor configuration A. AFMBR, B. AOFMBR and AeMBR. AeMBR and AOFMBR had the same reactor configuration except no GAC was added into AeMBR

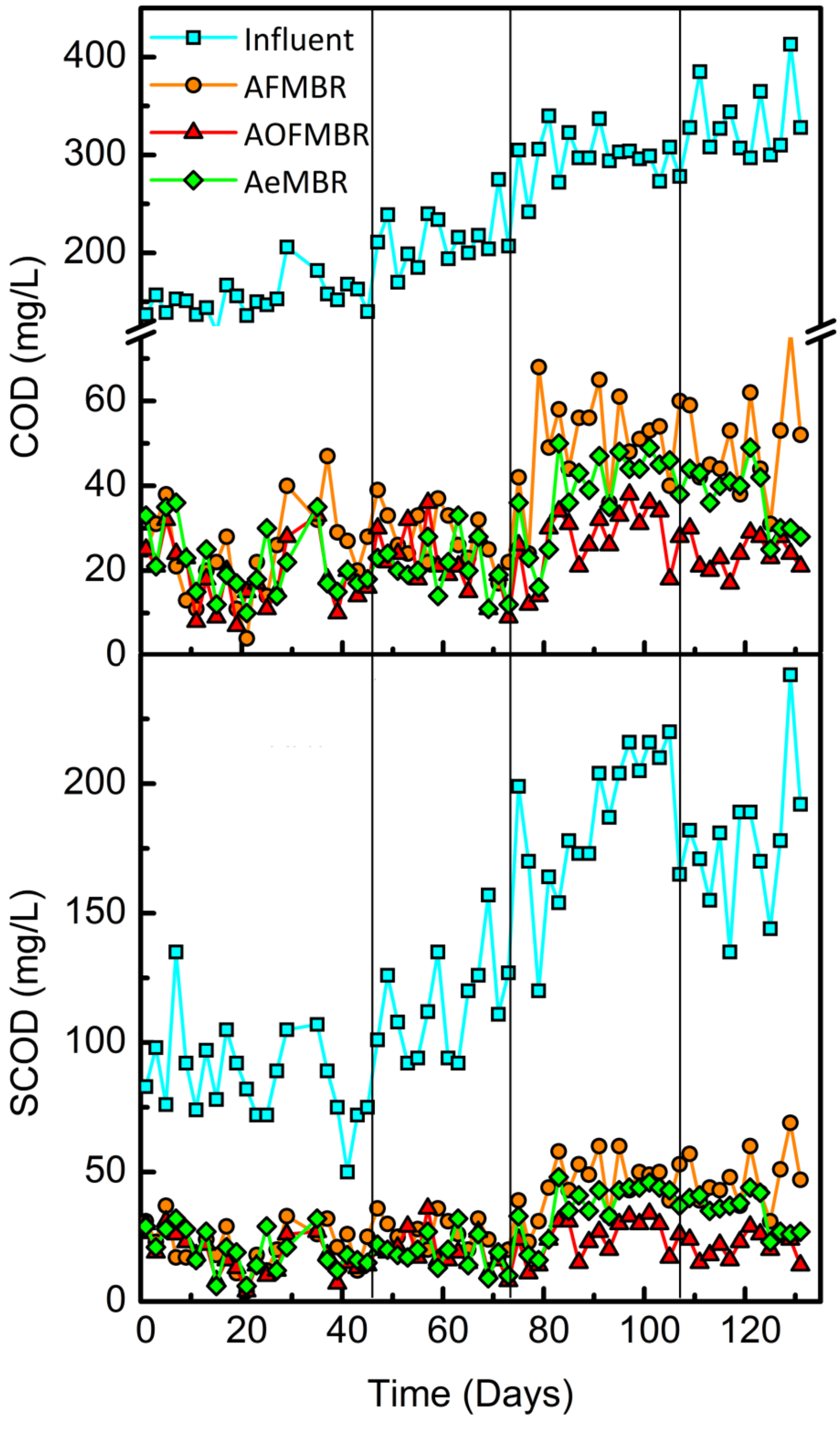

Fig. S2 – The effluent COD and SCOD over time

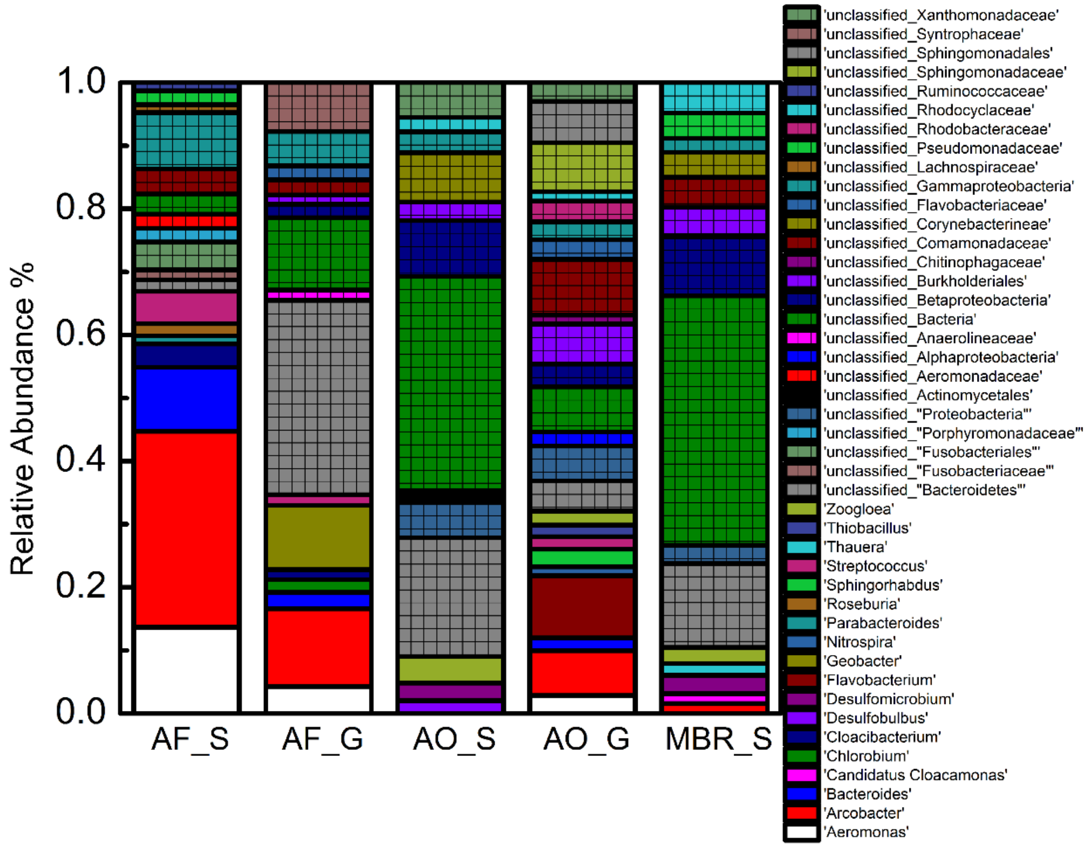

Fig. S3 – Analysis of the microbial communities in the solution (S) and on the GAC (G) in the AOFMBR (AO), AFMBR (AF) and AeMBR (MBR) reactors based on relative abundance at the genus level (removing genera at <1% abundance)

Energy calculations for the AFMBR and AOFMBR

The energy used by the AFMBR was estimated as described previously (Ren et al., 2014), except as noted below:

1. Influent pumping energy

The head increase due to the influent pumping is

$$\mathrm{H}_L = h + \frac{v^2}{2g} = h + \frac{(\frac{Q}{A})^2}{2g} = (0.5\ \mathrm{m}) + \frac{\left(\frac{\left(0.85\frac{\mathrm{cm^3}}{\mathrm{min}}\right)}{(\frac{\pi}{4})(0.6\ \mathrm{cm})^2}\frac{1\ \mathrm{min}}{60\ \mathrm{s}}\frac{1\ \mathrm{m}}{100\ \mathrm{cm}}\right)^2}{(2)\left(9.8\,\frac{\mathrm{m}}{\mathrm{s^2}}\right)} = 0.5\ \mathrm{m} \qquad \text{eq. 1}$$

where $h = 0.5$ m is the height difference between the pump and water surface level, and $v = 5 \times 10^{-4}$ m/s is the velocity of the influent, calculated from the inlet diameter of 0.6 cm and influent flow rate of 0.85 $\mathrm{cm^3}$/min. H_L is the headloss of the influent pumping.

The power and energy cost normalized to treated wastewater for influent pumping energy:

$$W_i = \rho g H_L Q = \left(1000\,\frac{\mathrm{kg}}{\mathrm{m^3}}\right)\left(9.8\frac{\mathrm{m}}{\mathrm{s^2}}\right)(0.5\ \mathrm{m})\left(0.85\frac{\mathrm{cm^3}}{\mathrm{min}}\right)\frac{1\ \mathrm{m^3}}{10^6\ \mathrm{cm^3}}\frac{1\ \mathrm{min}}{60\ \mathrm{s}}\frac{1\mathrm{W}}{\frac{1\ \mathrm{kg\ m^2}}{\mathrm{s^3}}}$$

$$= 7.0\ \times\ 10^{-5}\ W \qquad \text{eq. 2}$$

$$W_i^N = \frac{W_i}{Q} = \frac{(7.0\times10^{-5}\mathrm{W})\frac{1\ \mathrm{kW}}{1000\ \mathrm{W}}}{(0.85\frac{\mathrm{cm^3}}{\mathrm{min}})\frac{1\ \mathrm{m^3}}{10^6\ \mathrm{cm^3}}\frac{60\ \mathrm{min}}{1\ \mathrm{h}}} = 0.0014\,\frac{\mathrm{kWh}}{\mathrm{m^3}} \qquad \text{eq. 3}$$

where $H_L = 0.5\ \mathrm{m}$ is the total headloss of the influent pumping, and $\rho = 1000\ \mathrm{kg/m^3}$ is the density of the wastewater, and $Q = 0.85\ \mathrm{cm^3/min}$ is the flow rate of influent,. E_i represents the power required for influent pumping, and E_i^N is the normalized influent pumping energy cost for treating 1 $\mathrm{m^3}$ wastewater.

2. Effluent pumping energy

The transmembrane pressure on day 75 was chosen for this calculation as this was at the end of phase 2 where the TMP increase remains slow and linear, although other pressures could similarly be used to make this calculation.

The energy for effluent pumping energy:

$$W_e = \Delta P Q = (9 \times 10^3\ \mathrm{Pa})\left(0.85\frac{\mathrm{cm^3}}{\mathrm{min}}\right)\frac{1\ \mathrm{m^3}}{10^6\ \mathrm{cm^3}}\frac{1\ \mathrm{min}}{60\ \mathrm{s}}\frac{1\frac{\mathrm{kg}}{\mathrm{m\ s^2}}}{1\ \mathrm{Pa}}\frac{1\ \mathrm{W}}{1\frac{\mathrm{kg\ m^2}}{\mathrm{s^3}}} = 1.3 \times 10^{-4}\mathrm{W} \qquad \text{eq. 4}$$

$$W_e^N = \frac{W_e}{Q} = \frac{(1.3\times10^{-4}\mathrm{W})\frac{1\ \mathrm{kW}}{1000\ \mathrm{W}}}{(0.85\frac{\mathrm{cm^3}}{\mathrm{min}})\frac{1\ \mathrm{m^3}}{10^6\ \mathrm{cm^3}}\frac{60\ \mathrm{min}}{1\ \mathrm{h}}} = 0.0026\,\frac{\mathrm{kWh}}{\mathrm{m^3}} \qquad \text{eq. 5}$$

where $\Delta P = 9000$ Pa is the transmembrane pressure, and $\rho = 1000\ \mathrm{kg/m^3}$ is the density of the wastewater, and $Q = 0.85\ \mathrm{cm^3/min}$ is the effluent flow rate. E_i

represents the power required for effluent pumping, and E_e^N is the normalized effluent pumping energy cost for treating 1 m^3 wastewater.

3. Recirculation pumping energy

The headloss of GAC fluidization:

$$\Delta\mathrm{P} = \mathrm{g}(\rho_c - \rho_g)(1-\varepsilon)\mathrm{h}$$

$$= \left(9.8\frac{\mathrm{m}}{\mathrm{s}^2}\right)\left[(1300-1000)\frac{\mathrm{kg}}{\mathrm{m}^3}\right](1-0.75)(0.3\ \mathrm{m})\frac{1\ \mathrm{Pa}}{1\frac{\mathrm{kg}}{\mathrm{m\ s}^2}}$$

$$= 220.5\ \mathrm{Pa} \qquad \text{eq. 6}$$

$$H_L = \frac{\Delta\mathrm{P}}{\rho g} = \frac{(220.5\ \mathrm{Pa})\frac{1\frac{\mathrm{kg}}{\mathrm{m\ s}^2}}{1\ \mathrm{Pa}}}{(1000\frac{\mathrm{kg}}{\mathrm{m}^3})(9.8\frac{\mathrm{m}}{\mathrm{s}^2})} = 0.0225\ \mathrm{m} \qquad \text{eq. 7}$$

where $\rho_c = 1300\ \mathrm{kg}/m^3$ is the density of the GAC particle, and $\rho_g = 1000\ \mathrm{kg/m^3}$ is the density of the wastewater, and $\mathrm{h} = 0.3\ \mathrm{m}$ is the bed height in our reactor design, and $\varepsilon = \frac{\text{void volume}}{\text{void volume+media volume}} = 1 - \frac{\text{The settled bed height}}{\text{fluidized bed height}} = \frac{(30-7.5)\ \mathrm{cm}}{(30)\ \mathrm{cm}} = 0.75$ is the porosity of GAC fluidization, and $\Delta\mathrm{P}$ presents the pressure drop caused by GAC fluidization, and H_L is the corresponding headloss.

The headloss of the two tee connectors calculated by Darcy–Weisbach equation (not included in the previous study) (K value derived from *Water Transmission and Distribution WSO: Principles and Practices of Water Supply Operations, 2014, page 114*):

$$H_L = K\frac{v^2}{2g} = K\frac{(\frac{Q}{A})^2}{2g} = (2.4)\frac{\left(\frac{\left(250\frac{\mathrm{cm}^3}{\mathrm{min}}\right)\frac{1\ \mathrm{m}^3}{10^6\ \mathrm{cm}^3}\frac{1\ \mathrm{min}}{60\ \mathrm{s}}}{(\frac{\pi}{4})(1.5\ \mathrm{cm})^2 * \frac{1\ \mathrm{m}^2}{10^4\ \mathrm{cm}^2}}\right)^2}{(2)\left(9.8\frac{\mathrm{m}}{\mathrm{s}^2}\right)} = 7.1\times10^{-5}\ \mathrm{m} \qquad \text{eq. 8}$$

where $\mathrm{K} = 2.4$ is the friction coefficient for tee connectors, and $v = 2.4\ \mathrm{cm/s}$ is the recirculation velocity (calculated with the recirculation flow rate of 250 $\mathrm{cm^3}$/min and the crosssection diameter of 1.5 cm). H_L is the total headloss for the two tee connectors.

The headloss by flowing through the reactor estimated by Hazen-Williams Equation (not included in the previous study) (C value was obtained from Optimal Design of Water Distribution Networks, 2004, page 116):

$$H_L = \left(\frac{Q_r}{0.278CD^{2.63}}\right)^{\frac{1}{0.54}} L$$

$$= \left(\frac{\left(250\ \frac{\text{cm}^3}{\text{min}}\right)\frac{1\ \text{min}}{60\ \text{s}}}{(0.278\ \frac{\text{m}^{0.37}}{\text{s}})(140)(1.5\ \text{cm}\ \frac{1\ \text{m}}{100\ \text{cm}})^{2.63}}\right)^{\frac{1}{0.54}} (0.5\ \text{m})$$

$$= 4.8 \times 10^{-5}\ \text{m} \qquad \text{eq. 9}$$

where $Q_r = 250\ \text{cm}^3/\text{min}$ is the recirculation flow rate of, and $D = 1.5$ cm is the diameter of the pipe, and $C = 140$ (assumed) is Hazen-Williams constant. H_L is the headloss due to GAC fluidization.

The energy for maintaining GAC fluidization was calculated as:

$$W_r = \rho g H_{L,total} Q_r$$

$$= \left(1000\frac{\text{kg}}{\text{m}^3}\right)\left(9.8\frac{\text{m}}{\text{s}^2}\right)(0.0225\ \text{m} + 7.1 \times 10^{-5}\ \text{m} + 4.8 \times 10^{-5}\ \text{m})\left(250\frac{\text{cm}^3}{\text{min}}\right)\frac{1\ \text{min}}{60\ \text{s}}\frac{1\ \text{m}^3}{10^6\ \text{cm}^3}\frac{1\ \text{W}}{1\ \frac{\text{kg m}^2}{\text{s}^3}}$$

$$= 9.2 \times 10^{-4}\ \text{W} \qquad \text{eq. 10}$$

$$W_r^N = \frac{W_r}{Q} = \frac{(9.2\times10^{-4}\text{W})(\frac{1\ \text{kW}}{1000\ \text{W}})}{(0.85\frac{\text{cm}^3}{\text{min}})\frac{1\ \text{m}^3}{10^6\ \text{cm}^3}\frac{60\ \text{min}}{1\ \text{h}}} = 0.019\frac{\text{kWh}}{\text{m}^3} \qquad \text{eq. 11}$$

where $Q_r = 250\ \text{cm}^3/\text{min}$ is the recirculation flow rate, and $H_{L,total} = 0.0226$ m is the total headloss (calculated by summing up all the headloss), and $\rho = 1000\ \text{kg/m}^3$ is the density of the wastewater, , $Q = 0.85\ \text{cm}^3/\text{min}$ is the influent flow rate. E_r represents the power required for recirculation pumping, and E_r^N is the normalized recirculation pumping energy cost for treating 1 m^3 wastewater.

The influent and effluent pumping energy of AOFMBR and AeMBR were calculated with the same method as AFMBR. Influent pumping energy was estimated to be 0.0014 kWh/m^3 for both reactors, and the effluent pumping energy, 0.0013 kWh/m^3 (AOFMBR) and 0.0022 kWh/m^3 (AeMBR) (TMP of 4.5 kPa in AOFMBR and 7.5 kPa in AeMBR, day 75).

The air blower energy was estimated using:

$$W_a = \rho g H_L Q_a = \left(1000\frac{\text{kg}}{\text{m}^3}\right)\left(9.8\frac{\text{m}}{\text{s}^2}\right)(0.3\ \text{m})\left(240\frac{\text{cm}^3}{\text{min}}\right)\frac{1\ \text{min}}{60\ \text{s}}\frac{1\ \text{m}^3}{10^6\ \text{cm}^3}\frac{1\ \text{W}}{1\frac{\text{kg m}^2}{\text{s}^3}}$$

$$= 0.012\ \text{W} \qquad \text{eq. 12}$$

$$W_a^N = \frac{W_a}{Q} = \frac{(0.012\text{W})(\frac{1\ \text{kW}}{1000\ \text{W}})}{(0.85\frac{\text{cm}^3}{\text{min}})\frac{1\ \text{m}^3}{10^6\ \text{cm}^3}\frac{60\ \text{min}}{1\ \text{h}}} = 0.24\frac{\text{kWh}}{\text{m}^3} \qquad \text{eq. 13}$$

where $P = 30$ cm is the head at air inlet, and $Q_a = 240\ \mathrm{cm^3/min}$ is the air flow rate, and $Q = 0.85\ \mathrm{cm^3/min}$ is the flow rate. E_a represents the power required for air blowing, and E_a^N is the normalized energy cost of aeration for treating 1 m^3 wastewater.

Table S1 The effluent COD, SCOD and removal efficiencies (average ±SD) for the three reactors in the 131-day of operation for the four phases.

		COD (mg/L)	SCOD (mg/L)	COD removal (%)	SCOD removal (%)
Phase 1	AOFMBR	18±7	17±8	88±4	80±9
	AeMBR	22±8	20±8	86±5	77±9
	AFMBR	24±10	22±8	84±6	75±11
Phase 2	AOFMBR	18±7	17±8	90±3	82±2
	AeMBR	22±8	20±8	84±4	76±7
	AFMBR	24±10	22±8	90±3	82±7
Phase 3	AOFMBR	18±7	17±8	91±2	86±3
	AeMBR	22±8	20±8	87±3	80±5
	AFMBR	24±10	22±8	83±3	85±6
Phase 4	AOFMBR	18±7	17±8	93±2	88±3
	AeMBR	22±8	20±8	88±3	80±4
	AFMBR	24±10	22±8	85±3	76±5

Table S2 Examination of whether the effluent CODs among the reactors (AF-AFMBR, AO-AOFMBR, MBR-AeMBR) were significantly different. When p values (based on the Student's T-test) were smaller than 0.03, the effluents were not considered to be significantly different. Comparisons are made on the data shown in Figure 1.

	AF/AO	AO/MBR	AF/MBR
Phase 1	0.03	0.09	0.22
Phase 2	0.007	0.40	0.001
Phase 3	<0.001	0.002	0.002
Phase 4	<0.001	<0.001	0.002

Reference

Ren, L., Ahn, Y., Logan, B.E., 2014. A two-stage microbial fuel cell and anaerobic fluidized bed membrane bioreactor (MFC-AFMBR) system for effective domestic wastewater treatment. Environ. Sci. Technol. 48, 4199–4206.