

**Full-scale hybrid membrane aerated biofilm reactor (MABR) upgrade enhances the removal of organic micropollutants**

Narasimman Lakshminarasimman\*, Sondus Jamal, Leslie Bragg, Mark Servos, Wayne Parker

Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, ON, Canada

Department of Biology, University of Waterloo, Waterloo, ON, Canada

\*Current Affiliation: Stantec, Toronto, ON, Canada | [Narasimman.lakshminarasimman@stantec.com](mailto:Narasimman.lakshminarasimman@stantec.com)

**Supplemental Information**

**Table S1 – Plant operational data used in contaminant mass balance**

<b>Date</b>	<b>Plant influent flow (m<sup>3</sup>/d)</b>	<b>Return activated sludge 1 flow (m<sup>3</sup>/d)</b>	<b>Return activated sludge 2 flow (m<sup>3</sup>/d)</b>	<b>Waste activated sludge flow (m<sup>3</sup>/d)</b>	<b>Waste activated sludge total suspended solids (mg/L)</b>	<b>Plant influent total Suspended Solids (mg/L)</b>
14/Sep/20	5735	5691	0	332	4744	265
15/Sep/20	5487	5429	0	332	4744	265
16/Sep/20	5632	5581	0	332	4744	265
12/Oct/20	5986	5706	0	333	6428	245
13/Oct/20	5615	5312	0	334	6428	245
14/Oct/20	5585	5299	0	335	6428	245
9/Nov/20	5526	5273	0	230	5500	250
10/Nov/20	5432	5167	0	330	5500	250
11/Nov/20	5502	5212	0	332	5500	250
7/Dec/20	5821	5343	0	326	6172	221
8/Dec/20	5697	5228	0	325	6172	221
9/Dec/20	5675	5238	0	324	6172	221
11/Jan/21	5944	5014	0	317	7268	266
12/Jan/21	5881	4926	0	315	7268	266
13/Jan/21	5691	4863	0	312	7268	266
14/Feb/22	5800	4863	0	252	5664	303
15/Feb/22	5572	4805	0	297	5664	303
16/Feb/22	5640	4865	0	307	5664	303
14/Mar/22	6301	4622	0	329	5052	322
15/Mar/22	6243	4638	0	334	5052	322
16/Mar/22	5937	4517	0	189	5052	322
11/Apr/22	6337	4272	0	334	5052	233
12/Apr/22	5919	4467	0	176	5052	233
13/Apr/22	5998	4221	0	381	5052	233
16/May/22	6072	8450	0	310	6608	248
17/May/22	5877	8875	0	249	6608	248
18/May/22	5900	8803	0	204	6608	248
13/June/22	5913	8626	0	153	5823	275
14/June/22	5789	8544	0	241	5823	275
15/June/22	5949	8535	0	384	5823	275
11/Jul/22	5545	8252	0	300	4648	322
12/Jul/22	5523	4112	0	440	4648	322
13/Jul/22	5507	4320	0	307	4648	322
8/Aug/22	5755	6831	0	338	4623	225
9/Aug/22	5567	6870	0	404	4623	225
10/Aug/22	5555	6891	0	339	4623	225

**Table S1 – Plant operational data used in contaminant mass balance before upgrade (continued)**

<b>Date</b>	<b>Plant influent flow (m<sup>3</sup>/d)</b>	<b>Return activated sludge 1 flow (m<sup>3</sup>/d)</b>	<b>Return activated sludge 2 flow (m<sup>3</sup>/d)</b>	<b>Waste activated sludge flow (m<sup>3</sup>/d)</b>	<b>Waste activated sludge total suspended solids (mg/L)</b>	<b>Plant influent total Suspended Solids (mg/L)</b>
26/Sep/22	5873	4321	2152	238	4672	133
28/Sep/22	5725	4321	2139	320	4672	133
29/Sep/22	5690	4321	2139	258	4672	133
4/Oct/22	5677	4322	2237	238	5111	304
5/Oct/22	5742	4322	2247	402	5111	304
6/Oct/22	5601	4322	2186	225	5111	304
10/Oct/22	5837	4320	2195	197	5111	304
11/Oct/22	6031	4321	2258	131	5111	304
12/Oct/22	5447	4321	2323	88	5111	304
14/Nov/22	5668	4115	2183	106	5416	327
15/Nov/22	5871	4134	2180	344	5416	327
16/Nov/22	5450	4006	2098	269	5416	327
12/Dec/22	5498	4097	2107	261	5307	277
13/Dec/22	5599	3997	2107	339	5307	277
14/Dec/22	5304	4033	2172	185	5307	277
16/Jan/23	5824	4079	2138	213	6850	321
17/Jan/23	5824	4086	2139	254	6850	321
18/Jan/23	5699	4079	2138	288	6850	321
20/Mar/23	6597	4321	2145	233	6995	324
21/Mar/23	6434	4320	2137	235	6995	324
22/Mar/23	6516	4320	2139	235	6995	324
17/Apr/23	6479	4320	2144	297	6640	315
18/Apr/23	6200	4320	2156	274	6640	315
19/Apr/23	6206	4321	2194	264	6640	315
29/May/23	6126	4281	2132	276	5010	332
30/May/23	5962	4309	2133	216	5010	332
31/May/23	6049	4321	2150	229	5010	332
26/Jun/23	6172	4320	2124	295	5444	275
27/Jun/23	5988	4320	2208	272	5444	275
28/Jun/23	5813	4311	2147	159	5444	275
24/Jul/23	5861	4320	2139	263	5517	354
25/Jul/23	5668	4311	2137	268	5517	354
26/Jul/23	5739	4320	2146	267	5517	354
21/Aug/23	6125	4184	0	193	5790	365
25/Aug/23	7345	5344	0	316	5790	365
28/Aug/23	6303	4791	0	274	5790	365

18/Sep/23	5992	4637	0	218	5600	225
19/Sep/23	5681	4428	0	235	5600	225
20/Sep/23	5828	4510	0	278	5600	225

**Table S2 – Summary of the solid phase extraction methods**

<b>Parameter</b>	<b>PPCP method</b>	<b>Hormones method</b>
Sample volume	100 mL	
	Manual manifold set up	Automated SPE
Replicate per sample	Triplicate	Duplicate
Acidification	Using 10 N HCl for pH 2 ± 0.1	No acidification
Cartridge	Bond Elut Plexa cartridges (6 cc, 500 mg, Agilent)	Superclean LC18 cartridges (6 cc, 500 mg, Sigma Aldrich)
Conditioning	5 mL Methanol + 5 mL MilliQ Water	5 mL Methanol + 5 mL MilliQ Water
Elution	3 mL Methanol + 3 mL Methanol	5 mL Ethylacetate + 5 mL Ethylacetate
Evaporation	Evaporation to dryness under a gentle stream of N <sub>2</sub> gas	
Reconstitution	Methanol with 75 µg/L lorazepam and chloramphenicol as instrument controls	Methanol
Final volume	0.5 mL	

**Table S3 – Matrix spike recovery for the target compounds**

<b>OMP</b>	<b>Recovery of matrix spike in % (Average ± standard deviation)</b>
NPX	100 ± 12
DCF	99 ± 7
IBU	99 ± 12
GFZ	100 ± 5
TCCB	100 ± 5
TCS	100 ± 7
ACE	104 ± 42
SULF	104 ± 27
CAFF	106 ± 67
TRIM	103 ± 31
CBZ	104 ± 28
p-ATOR	102 ± 22
NFLX	97 ± 37
FLX	98 ± 20
o-ATOR	101 ± 24
ATOR	101 ± 26
E1	104 ± 42
E2	101 ± 14
E3	99 ± 15
BPA	99 ± 15

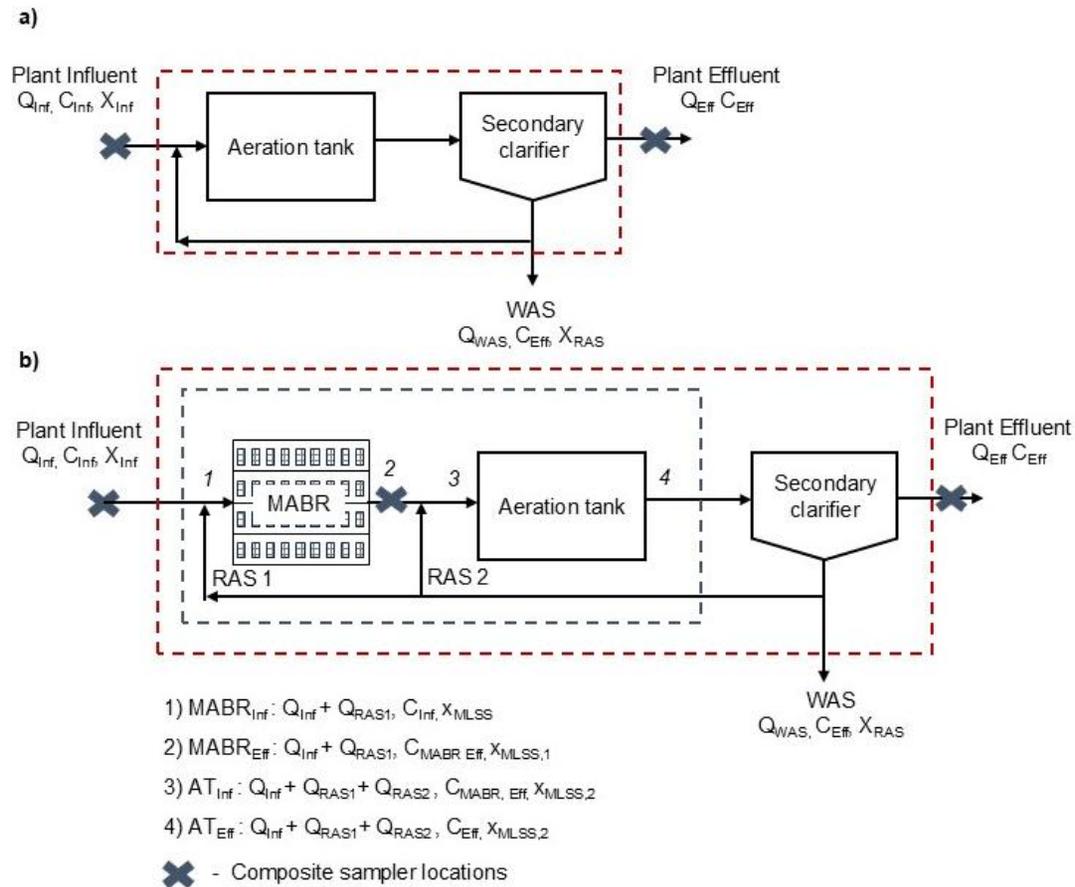
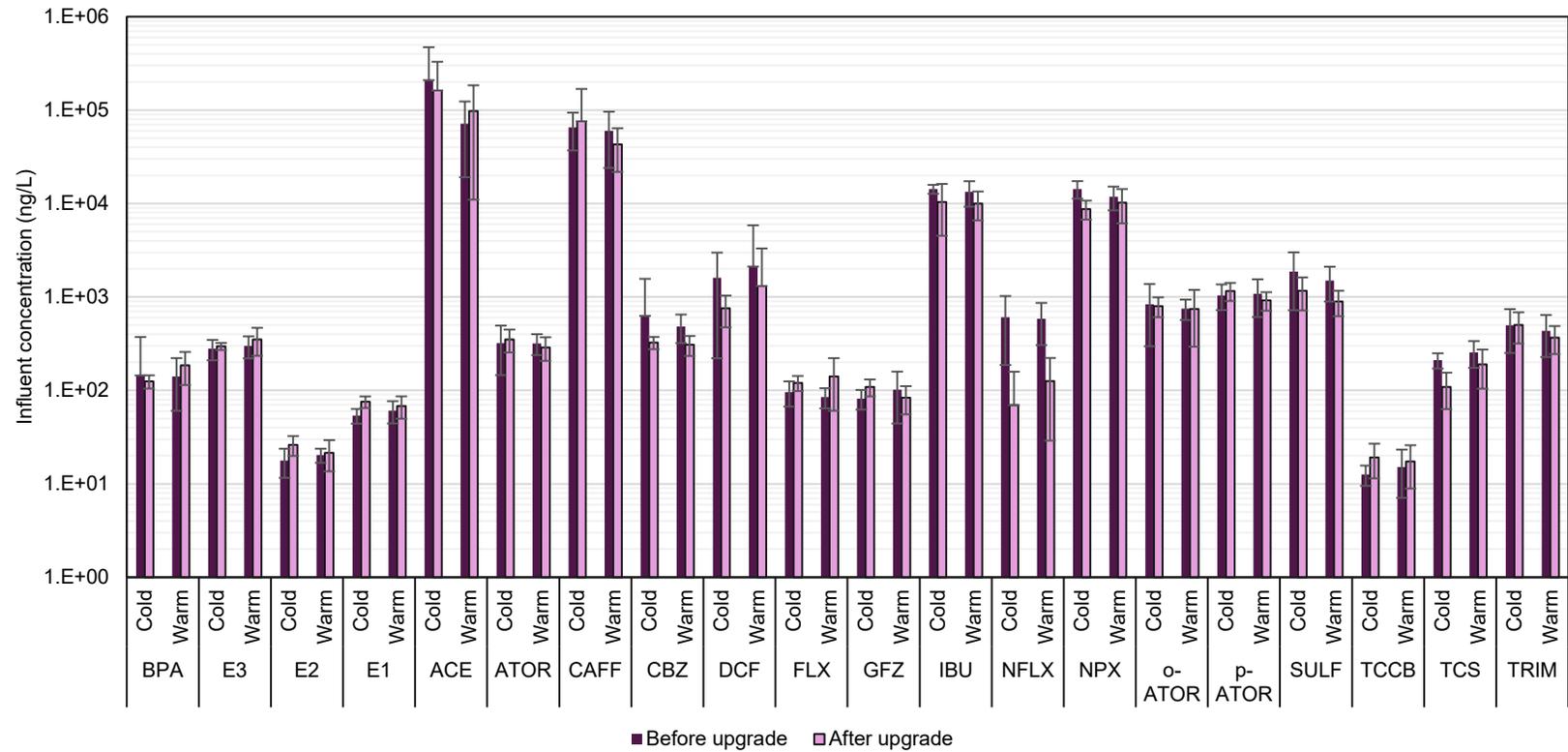


Figure S1 – System boundaries for two mass balance analyses performed in this study



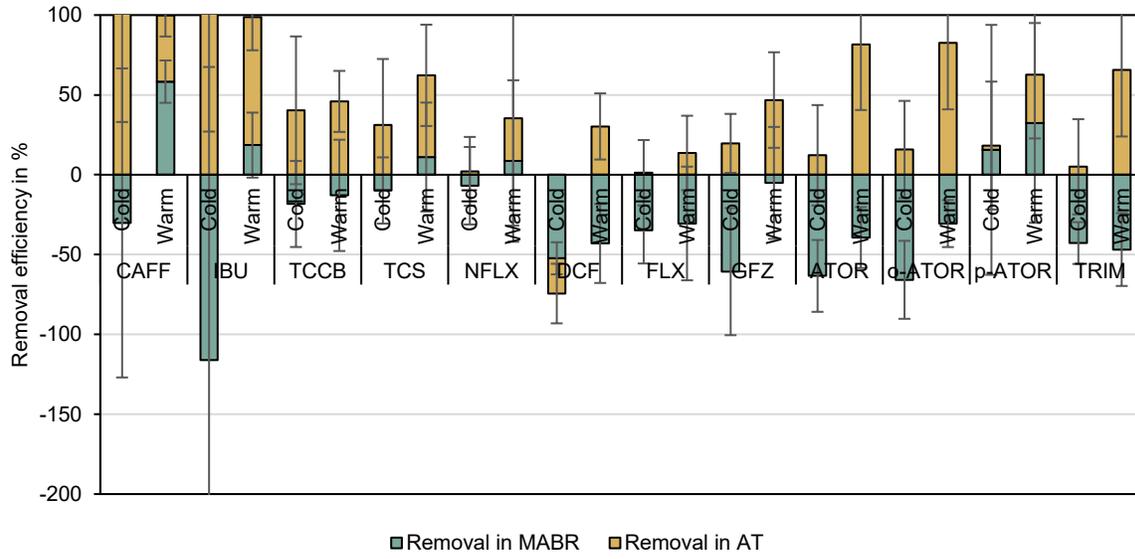
**Figure S2 – Influent OMP concentrations before and after the upgrade during warm and cold weather conditions.**

**Table S4 – Compounds that showed significant differences in average effluent concentrations between the categories assessed.**

Operating conditions		Before upgrade		After upgrade	
		Cold	Warm	Cold	Warm
Before upgrade	Cold				
	Warm	NLX			
After upgrade	Cold	CAFF	TCS		
	Warm	TCS, GFZ, ATOR, o-ATOR, p-ATOR, NFLX, TMP	CAFF, IBU, NPX, TCCB, TCS, GFZ, ATOR, o-ATOR, p-ATOR, SULF, TRIM, CBZ	TCS, GFZ, ATOR, o-ATOR, p-ATOR, NFLX, TRIM, E1	

**Table S5 – Co-efficient of variation in the plant influent OMP concentration across the four operational scenarios studied**

<b>Organic micropollutant</b>	<b>Seasonal condition</b>	<b>Pre upgrade (%)</b>	<b>Post upgrade (%)</b>
BPA	Cold	158	16
	Warm	57	39
E3	Cold	25	9
	Warm	26	33
E2	Cold	34	24
	Warm	17	37
E1	Cold	18	14
	Warm	27	27
ACE	Cold	125	103
	Warm	73	89
ATOR	Cold	54	27
	Warm	25	28
CAFF	Cold	44	122
	Warm	60	49
CBZ	Cold	149	15
	Warm	34	24
DCF	Cold	86	37
	Warm	176	152
FLX	Cold	30	18
	Warm	24	57
GFZ	Cold	24	21
	Warm	56	33
IBU	Cold	11	56
	Warm	30	34
NFLX	Cold	69	128
	Warm	48	77
NPX	Cold	21	23
	Warm	28	40
p-ATOR	Cold	65	24
	Warm	25	60
SULF	Cold	31	22
	Warm	43	22
TCCB	Cold	61	39
	Warm	41	31
TCS	Cold	24	40
	Warm	53	49
TRIM	Cold	19	42
	Warm	32	45



**Figure S3 - Removal through biotransformation in MABR and aeration tank**