Supporting Information

Nursery Runoff Treatment by Novel Biochar Amended Bioretention Systems
(Richardson et. al, 2024)

SI Materials and Methods

Pilot-Scale Bioretention Systems

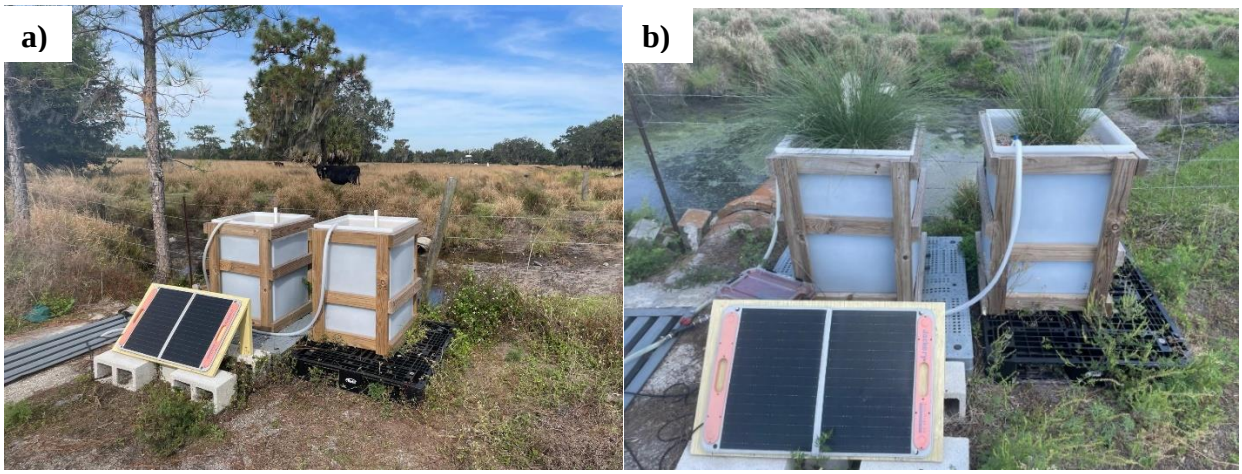


Figure S1. Bioretention systems (**a**) CBA (left) and PBA (right) (**b**) CBA+P (left) and PBA+P (right).

Table S1. Summary of bioretention monitoring runoff events.

Event #	Date	HLR (cm/min)	Estimated % Area covered	Outlet Used	Muhly Grass Presence
1	6-Sep-23	0.109	5	Lower	No
2	12-Sep-23	0.109	5	Lower	No
3	26-Sep-23	0.109	5	Lower	No
4	18-Oct-23	0.217	2.5	Lower	No
5	25-Oct-23	0.217	2.5	Lower	No
6 *	31-Oct-23	0.217	2.5	Lower	No
7	3-Nov-23	0.544	1	Lower	No
8	8-Nov-23	0.544	1	Lower	No
9 *	16-Nov-23	0.544	1	Lower	No
10 *	20-Nov-23	0.544	1	Upper	No
11	29-Nov-23	0.544	1	Upper	No

12	6-Dec-23	0.544	1	Upper	No
13 *	22-Jan-24	0.544	1	Lower	Yes
14	31-Jan-24	0.544	1	Lower	Yes
15	8-Feb-24	0.544	1	Lower	Yes
16	20-Mar-24	0.217	2.5	Upper	Yes
17	10-Apr-24	0.217	2.5	Upper	Yes
18	18-Apr-24	0.217	2.5	Upper	Yes

* Represents that the influent runoff was leftover water in the slough backed up by the weir

Equation S1. Mean Residence Time (MRT) [min]. C represents the effluent tracer concentration (mg KCl/L), and t represents time (min).

$$MRT = \frac{\int_0^\infty Ct\ dt}{\int_0^\infty C\ dt} \tag{S1}$$

Equation S2. Time in terms of MRTs (Θ).

$$\Theta = \frac{t}{MRT} \tag{S2}$$

Equation S3. % Mass Recovered. Q represents the flow rate through the system (L/min). The mass of KCl added at the beginning of each event was 20 grams.

$$\%\ Mass\ Recovered = \frac{\int_0^\infty QCtdt}{20{,}000\ milligrams} \cdot 100\% \tag{S3}$$

Equation S4. Time of 10% Mass recovered (t_{10}).

$$10\% = \frac{\int_0^\infty QCt_{10}\ dt}{20{,}000\ milligrams} \cdot 100\% \tag{S4}$$

Equation S5. Time of 50% Mass recovered (t_{50}).

$$50\% = \frac{\int_0^\infty QCt_{50}\ dt}{20{,}000\ milligrams} \cdot 100\% \tag{S5}$$

Equation S6. Time of 90% Mass recovered (t_{90}).

$$90\% = \frac{\int_0^\infty QCt_{90}\ dt}{20{,}000\ milligrams} \cdot 100\% \tag{S6}$$

Equation S7. Morril dispersion Index (MDI) [-].

$$MDI = \frac{t_{90}}{t_{10}} \tag{S7}$$

Equation S8. Number of tanks in series (TIS n) [-].

$$TIS\,n = 1 + 1/\sigma_\theta^2 \tag{S8}$$

Equation S9. Variance (min^2).

$$\sigma_t^2 = \frac{\int_0^\infty C\ (t - MRT)^2\ dt}{\int_0^\infty C\ dt} \tag{S9}$$

Equation S10. Variance (Θ^2).

$$\sigma_\theta^2 = \frac{\sigma_t^2}{MRT^2} \tag{S10}$$

Equation S9. Standard Deviation (min).

$$\sigma_t = \sqrt{\sigma_t^2} \tag{S9}$$

Equation S10. Standard Deviation (Θ).

$$\sigma_\theta = \sqrt{\sigma_\theta^2} \tag{S10}$$

Equation S11. Cumulative Exit Mass (mg).

$$Cumulative\ Exit\ Mass = \int_0^\theta QC\theta d\theta \tag{S11}$$

Equation S12. Cumulative Tracer Exit Mass Fraction (F) [-].

$$F = \frac{\int_0^\theta QC\theta d\theta}{\int_0^\infty QC\theta d\theta} \tag{S12}$$

Equation S13. Equalized Tracer Concentration (E) [-].

$$E = \frac{dF}{d\theta} \tag{S13}$$

SI Results and Discussion

Runoff characterization

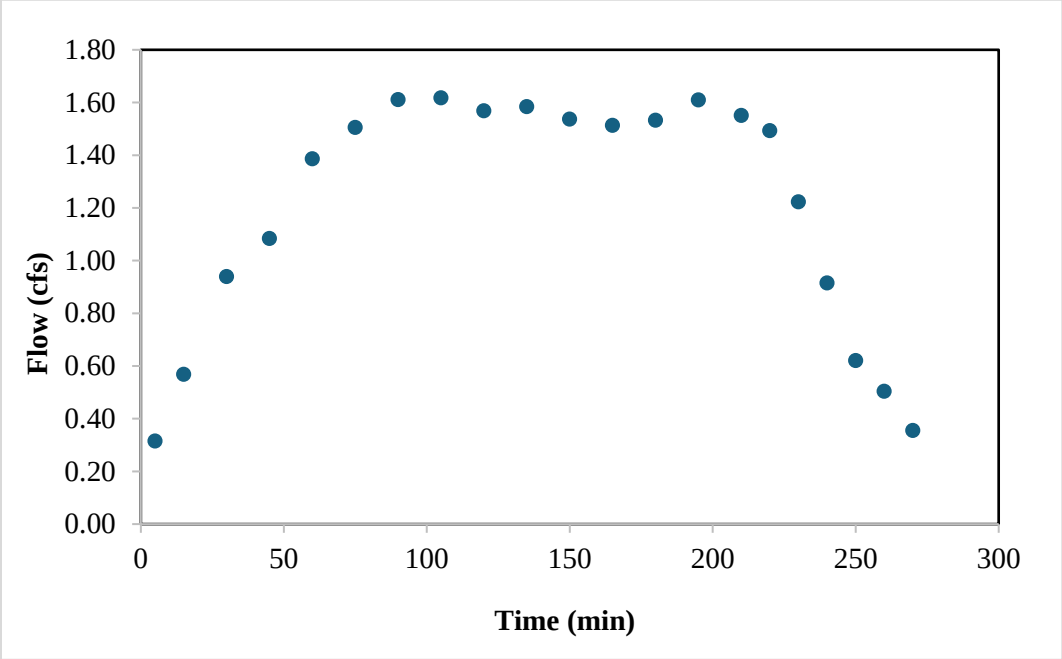


Figure S2. Runoff flow rate (in cfs) over time during an irrigation event. Steady state at 75–220 min and peaking at 1.574 cfs.

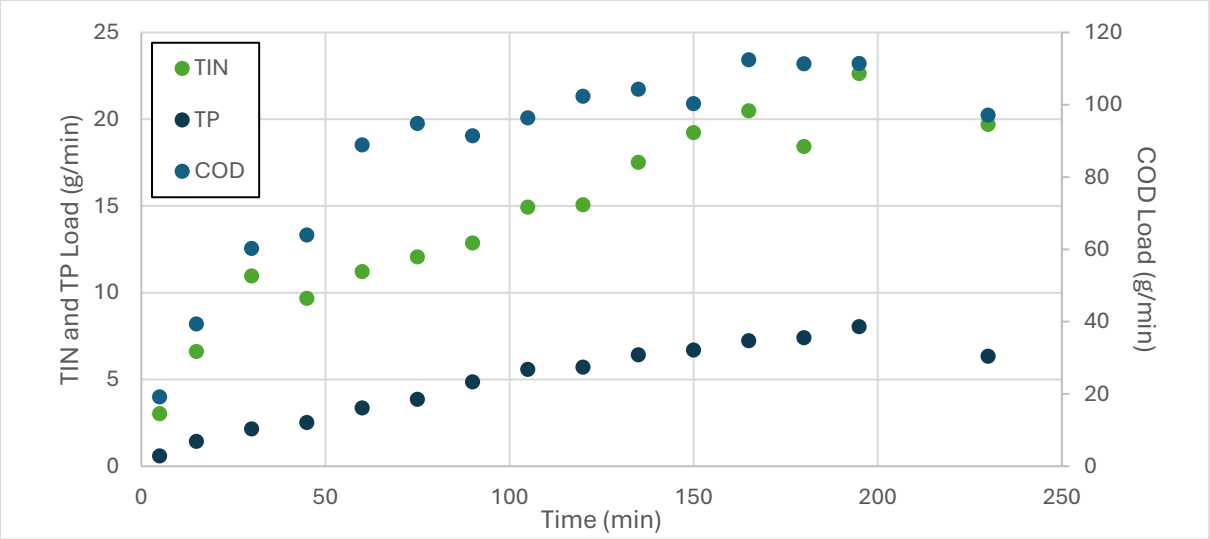


Figure S3. Runoff TIN, TP, and COD loads (g/min) over time.

Tracer Studies and Hydraulic Performance

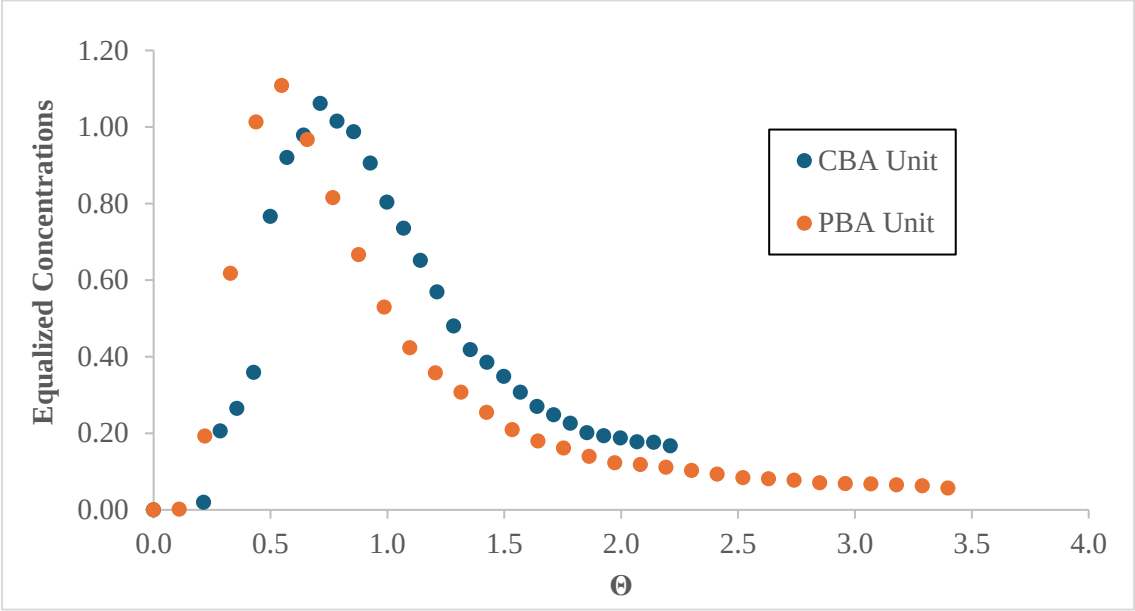


Figure S4. Equalized tracer concentrations (-) over Θ (-) for bioretention systems configured at their lower outlets.

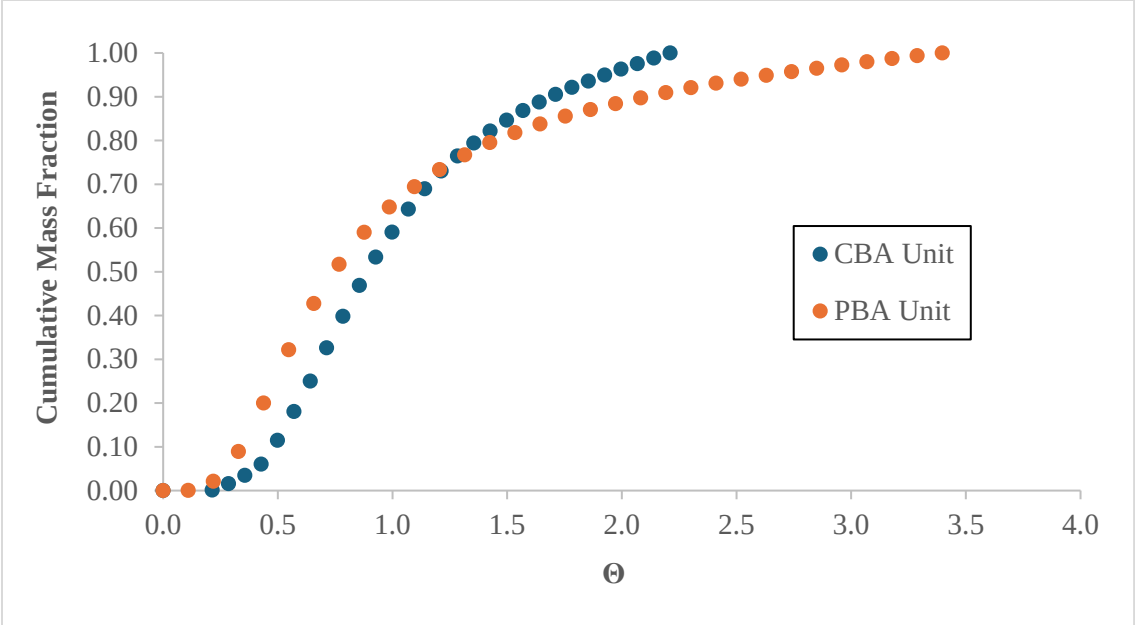


Figure S5. Cumulative tracer mass fraction exported (-) over Θ (-) for bioretention systems configured at their lower outlets.

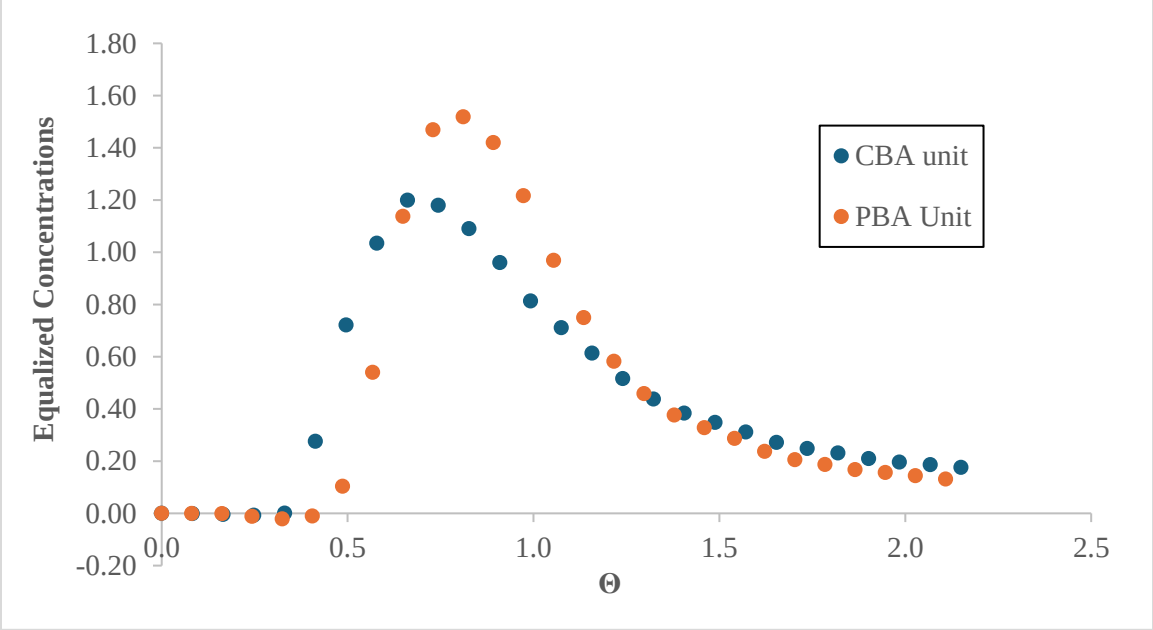


Figure S6. Equalized tracer concentrations (-) over Θ (-) for bioretention systems configured at their upper outlets.

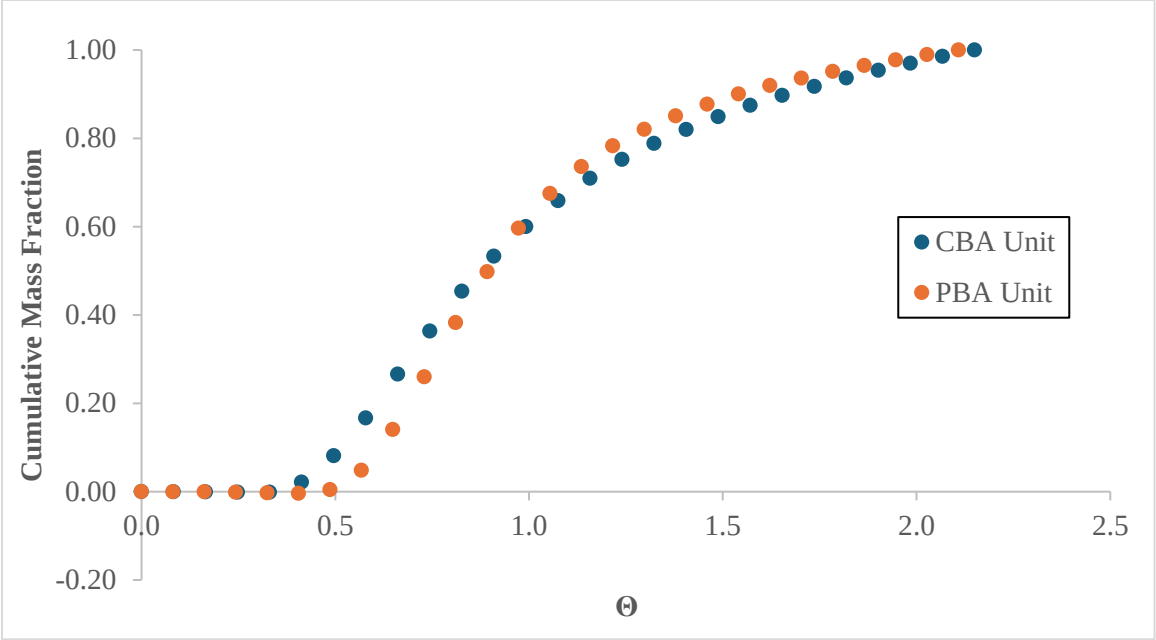


Figure S7. Tracer cumulative mass fraction exported (-) over Θ (-) for bioretention systems configured at their upper outlets.

Table S2. Flow rates (L/min) measured during tracer studies.

Unit	Outlet Configuration	Flow Rate (L/min)
CBA	Upper	2.07
PBA	Upper	1.85
CBA	Lower	1.16
PBA	Lower	1.06

Table S3. Raw influent (linearized for values every 5 minutes) and effluent specific conductivities, and converted effluent tracer concentrations (mg/L KCl) for tracer studies performed with the upper outlet height configuration.

	Linearized Influent Specific Conductivity (mS/cm)		Effluent Specific Conductivity (mS/cm)		Equalized Effluent Tracer Concentration (mg KCl/L)	
Time (min)	CBA Unit	PBA Unit	CBA Unit	PBA Unit	CBA Unit	PBA Unit
0	0.525	0.519	0.525	0.519	0.00	0.00
5	0.523	0.518	0.524	0.518	-0.52	-0.21

10	0.521	0.517	0.523	0.518	-1.04	-0.42
15	0.519	0.511	0.522	0.517	-1.56	-3.74
20	0.523	0.510	0.520	0.516	1.66	-3.94
25	0.664	0.516	0.519	0.516	90.17	0.21
30	0.759	0.574	0.518	0.515	150.05	36.73
35	0.829	0.765	0.517	0.514	194.35	156.07
40	0.845	0.916	0.516	0.514	205.04	250.49
45	0.816	0.954	0.515	0.513	187.71	274.57
50	0.795	0.943	0.513	0.512	175.37	268.13
55	0.744	0.896	0.512	0.512	144.34	239.29
60	0.714	0.825	0.511	0.511	126.39	195.50
65	0.684	0.749	0.507	0.507	110.20	150.67
70	0.654	0.691	0.503	0.503	94.01	117.05
75	0.624	0.645	0.499	0.499	77.83	90.90
80	0.604	0.612	0.495	0.495	67.86	72.84
85	0.587	0.590	0.491	0.491	59.77	61.64
90	0.577	0.576	0.487	0.487	56.03	55.41
95	0.562	0.561	0.486	0.486	47.53	46.90
100	0.553	0.545	0.484	0.484	42.75	37.77
105	0.547	0.540	0.483	0.483	39.85	35.49
110	0.541	0.532	0.482	0.482	36.94	31.34
115	0.533	0.526	0.480	0.480	32.79	28.43
120	0.531	0.523	0.479	0.479	32.38	27.39
125	0.526	0.517	0.478	0.478	29.68	24.07
130	0.524	0.514	0.478	0.478	28.85	22.62

Table S4. Raw influent (linearized for values every 5 minutes) and effluent specific conductivities, and converted effluent tracer concentrations (mg/L KCl) for tracer studies performed with the lower outlet height configuration.

	Linearized Influent Specific Conductivity (mS/cm)		Effluent Specific Conductivity (mS/cm)		Equalized Effluent Tracer Concentration (mg KCl/L)	
Time (min)	CBA Unit	PBA Unit	CBA Unit	PBA Unit	CBA Unit	PBA Unit
5	0.538	0.540	0.541	0.538	-2.08	1.15
10	0.541	0.785	0.540	0.537	0.83	154.21
15	0.552	1.090	0.538	0.536	8.72	344.63
20	0.685	1.296	0.536	0.536	92.56	473.42
25	0.595	1.212	0.535	0.535	37.56	421.64
30	0.756	1.111	0.533	0.534	138.84	359.29
35	0.913	1.014	0.531	0.533	237.63	299.11
40	0.874	0.916	0.530	0.532	214.38	238.93
45	0.956	0.834	0.528	0.531	266.47	188.41
50	0.931	0.777	0.521	0.531	255.06	153.45
55	0.906	0.747	0.515	0.530	243.64	135.30
60	0.896	0.710	0.508	0.529	241.57	112.79
65	0.828	0.677	0.501	0.528	203.38	92.77
70	0.802	0.644	0.495	0.521	191.35	76.37
75	0.761	0.625	0.488	0.515	169.97	68.69
80	0.728	0.607	0.487	0.508	150.05	61.64
85	0.694	0.583	0.486	0.501	129.50	50.85
90	0.656	0.572	0.485	0.495	106.46	48.15
95	0.643	0.564	0.484	0.488	98.99	47.32
100	0.628	0.555	0.483	0.487	90.28	42.34
105	0.612	0.551	0.482	0.486	80.94	40.47
110	0.594	0.541	0.482	0.485	69.94	34.87
115	0.582	0.537	0.481	0.484	62.68	33.00
120	0.576	0.535	0.481	0.483	59.15	32.38
125	0.564	0.530	0.481	0.482	51.88	29.88
130	0.556	0.525	0.480	0.482	47.11	26.98

135	0.557	0.527	0.480	0.481	47.94	28.43
140	0.551	0.523	0.480	0.481	44.20	26.15
145	0.549	0.523	0.480	0.481	42.96	26.36
150	0.550	0.519	0.480	0.480	43.58	24.07
155	0.542	0.515	0.480	0.480	38.60	21.79

Table S5. Theta, Cumulative tracer exit mass, Cumulative exit mass fraction (F), and Equalized tracer concentrations (E) from the tracer studies with the upper outlet configuration.

	Θ		**Cumulative Tracer Exit Mass (mg)**		**Cumulative Exit Mass Fraction (F) (-)**		**Equalized Tracer Concentration (E) (-)**	
Time (min)	**CBA Unit**	**PBA Unit**	**CBA Unit**	**PBA Unit**	**CBA Unit**	**PBA Unit**	**CBA Unit**	**PBA Unit**
0	0.00	0.00	0	0	0.00	0.00	0.00	0.00
5	0.08	0.08	-1	-1	0.00	0.00	0.00	0.00
10	0.17	0.16	-5	-2	0.00	0.00	0.00	0.00
15	0.25	0.24	-12	-12	0.00	0.00	-0.01	-0.01
20	0.33	0.32	-11	-32	0.00	0.00	0.00	-0.02
25	0.41	0.41	218	-41	0.02	0.00	0.28	-0.01
30	0.50	0.49	819	51	0.08	0.00	0.72	0.10
35	0.58	0.57	1680	533	0.17	0.05	1.03	0.54
40	0.66	0.65	2678	1550	0.27	0.14	1.20	1.14
45	0.74	0.73	3660	2862	0.36	0.26	1.18	1.47
50	0.83	0.81	4568	4219	0.45	0.38	1.09	1.52
55	0.91	0.89	5367	5488	0.53	0.50	0.96	1.42
60	0.99	0.97	6044	6575	0.60	0.60	0.81	1.22
65	1.07	1.05	6635	7440	0.66	0.68	0.71	0.97
70	1.16	1.14	7146	8109	0.71	0.74	0.61	0.75
75	1.24	1.22	7575	8629	0.75	0.78	0.52	0.58
80	1.32	1.30	7940	9039	0.79	0.82	0.44	0.46
85	1.41	1.38	8259	9375	0.82	0.85	0.38	0.38
90	1.49	1.46	8548	9667	0.85	0.88	0.35	0.33
95	1.57	1.54	8807	9923	0.87	0.90	0.31	0.29

100	1.65	1.62	9033	10135	0.90	0.92	0.27	0.24
105	1.74	1.70	9239	10318	0.92	0.94	0.25	0.20
110	1.82	1.78	9431	10485	0.94	0.95	0.23	0.19
115	1.90	1.87	9606	10635	0.95	0.97	0.21	0.17
120	1.98	1.95	9769	10774	0.97	0.98	0.20	0.16
125	2.07	2.03	9924	10903	0.99	0.99	0.19	0.14
130	2.15	2.11	10070	11020	1.00	1.00	0.18	0.13

Table S6. Theta, Cumulative tracer exit mass, Cumulative exit mass fraction (F), and Equalized tracer concentrations (E) from the tracer studies with the lower outlet configuration.

	Θ		**Cumulative Tracer Exit Mass (mg)**		**Cumulative Exit Mass Fraction (F) (-)**		**Equalized Tracer Concentration (E) (-)**	
Time (min)	**CBA Unit**	**PBA Unit**	**CBA Unit**	**PBA Unit**	**CBA Unit**	**PBA Unit**	**CBA Unit**	**PBA Unit**
0	0.00	0.00	0	0	0.00	0.00	0.00	0.00
5	0.04	0.04	1	3	0.00	0.00	0.00	0.00
10	0.08	0.09	-2	391	0.00	0.02	0.00	0.48
15	0.12	0.13	22	1638	0.00	0.09	0.03	1.55
20	0.16	0.17	275	3684	0.02	0.20	0.37	2.55
25	0.20	0.22	600	5921	0.03	0.32	0.48	2.79
30	0.24	0.26	1041	7873	0.06	0.43	0.65	2.43
35	0.28	0.31	1982	9519	0.12	0.52	1.38	2.05
40	0.32	0.35	3112	10865	0.18	0.59	1.65	1.67
45	0.36	0.39	4315	11933	0.25	0.65	1.76	1.33
50	0.40	0.44	5618	12788	0.33	0.69	1.91	1.06
55	0.44	0.48	6865	13509	0.40	0.73	1.82	0.90
60	0.48	0.52	8078	14130	0.47	0.77	1.78	0.77
65	0.52	0.57	9191	14644	0.53	0.79	1.63	0.64
70	0.56	0.61	10177	15066	0.59	0.82	1.44	0.53
75	0.59	0.65	11081	15429	0.64	0.84	1.32	0.45
80	0.63	0.70	11881	15755	0.69	0.86	1.17	0.41
85	0.67	0.74	12580	16036	0.73	0.87	1.02	0.35
90	0.71	0.78	13170	16284	0.76	0.88	0.86	0.31
95	0.75	0.83	13683	16522	0.79	0.90	0.75	0.30
100	0.79	0.87	14156	16746	0.82	0.91	0.69	0.28
105	0.83	0.92	14584	16953	0.85	0.92	0.63	0.26
110	0.87	0.96	14962	17142	0.87	0.93	0.55	0.23
115	0.91	1.00	15293	17311	0.89	0.94	0.49	0.21

120	0.95	1.05	15598	17475	0.91	0.95	0.45	0.20
125	0.99	1.09	15875	17630	0.92	0.96	0.41	0.19
130	1.03	1.13	16123	17773	0.94	0.96	0.36	0.18
135	1.07	1.18	16360	17911	0.95	0.97	0.35	0.17
140	1.11	1.22	16591	18048	0.96	0.98	0.34	0.17
145	1.15	1.26	16809	18179	0.98	0.99	0.32	0.16
150	1.19	1.31	17025	18305	0.99	0.99	0.32	0.16
155	1.23	1.35	17230	18420	1.00	1.00	0.30	0.14

Nitrogen Removal

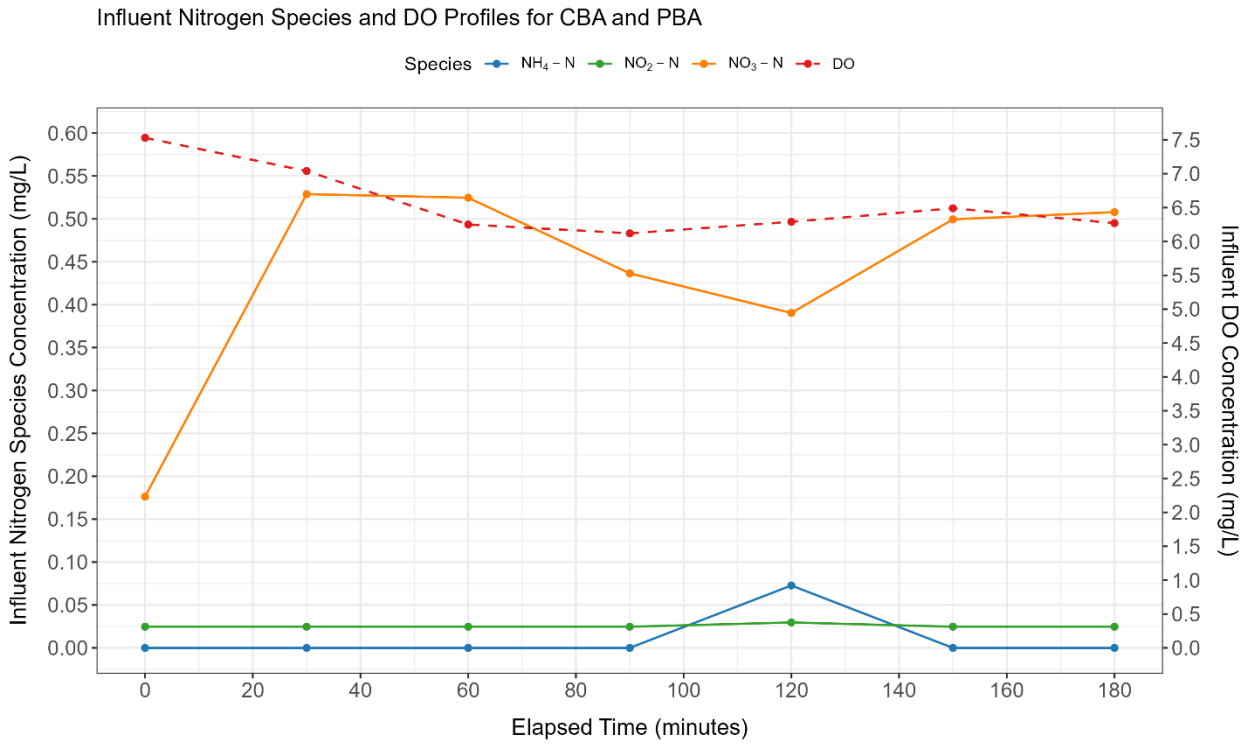


Figure S8. Influent NH_4^+-N, NO_2^--N, NO_3^--N, and DO concentrations over time during bioretention monitoring event eight.

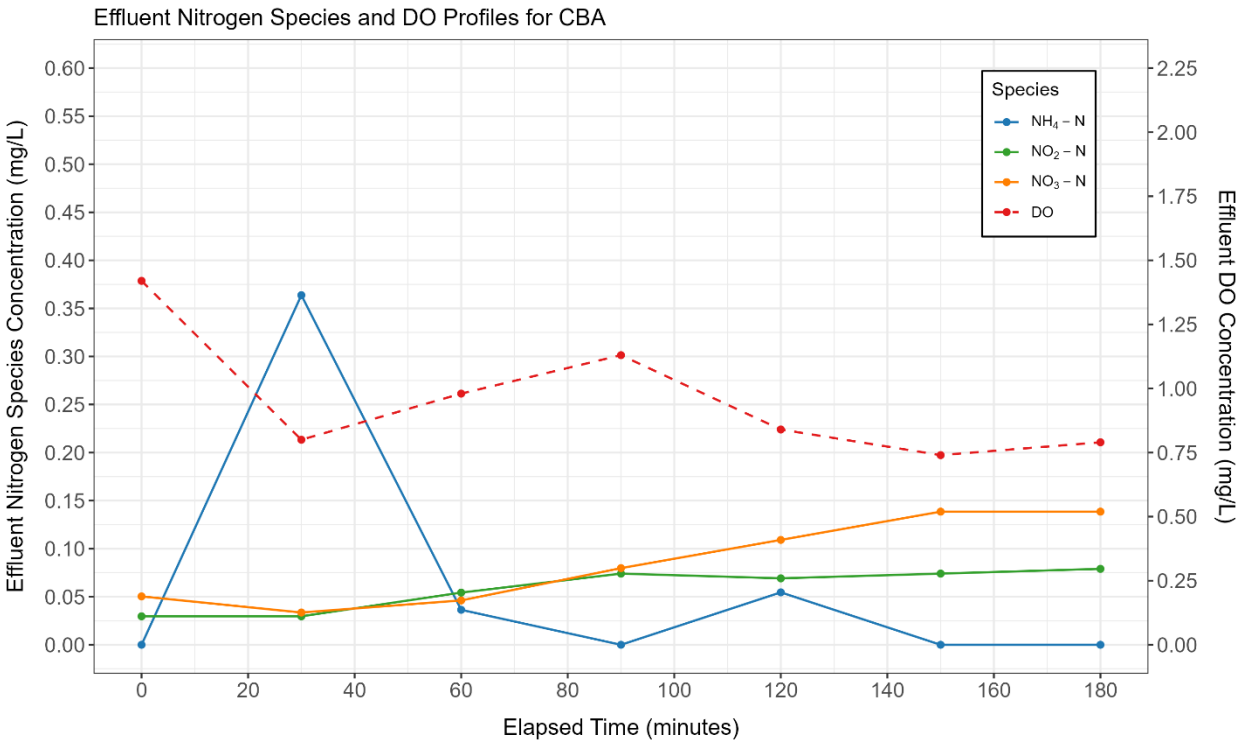


Figure S9. CBA effluent NH_4^+-N, NO_2^--N, NO_3^--N, and DO concentrations over time during bioretention monitoring event eight.

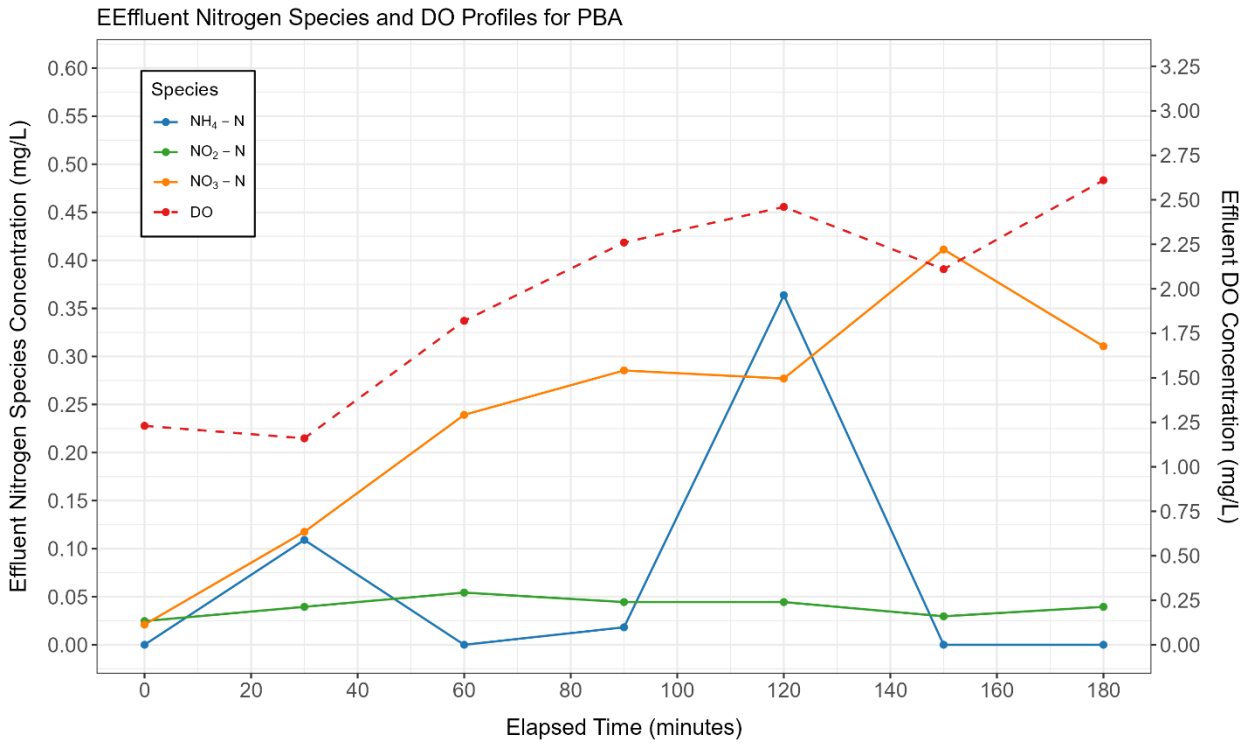


Figure S10. PBA effluent NH_4^+-N, NO_2^--N, NO_3^--N, and DO concentrations over time during bioretention monitoring event eight.

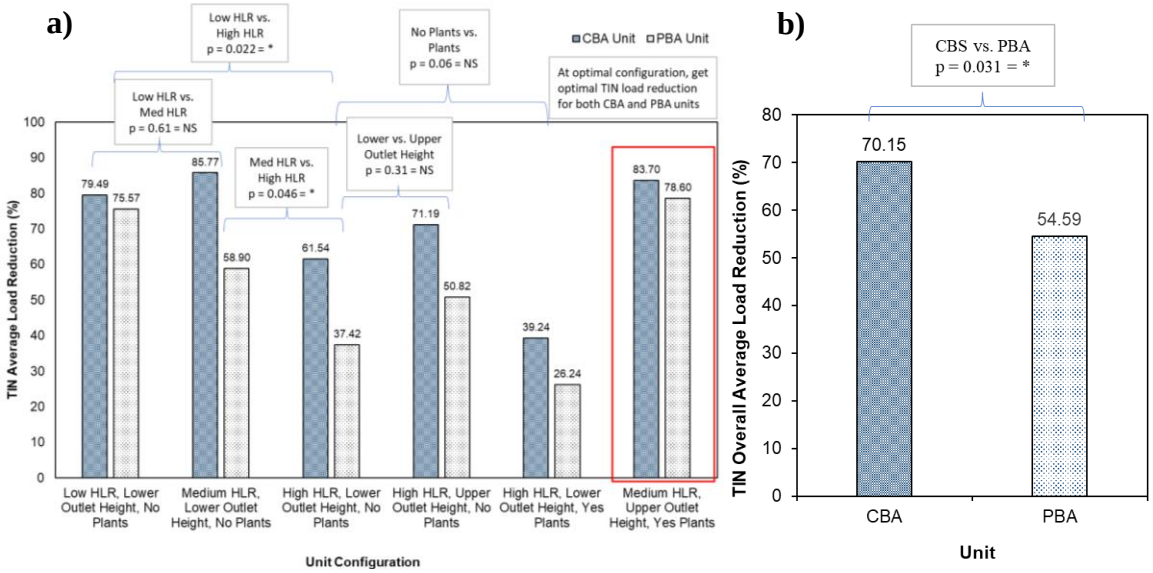


Figure S11. Average total inorganic nitrogen load reductions for all events and units, with ANOVA p-values (* for $p<0.05$, NS = not significant). The red box indicates a system operating at optimal configuration, where the Medium HLR demonstrates the best performance in terms of cost-effectiveness. b) Bar chart comparing total TIN load reductions between CBA and PBA units.

Modeling

This study uses a data-driven approach to model bioretention pollutant removal efficiency (NRR against NLR) across various configurations and design features. The fitted regression models employ different outlier-handling techniques, each represented by a distinct line (Figure):

- Black Solid Line: Represents the model fitted using standard linear regression. This method assumes all data points have equal influence and provides a baseline for comparison with other methods.
- Red Dotted Line (Refit Line): Represents a regression model recalculated after removing influential points identified using Cook's Distance. Cook's Distance measures the influence of each observation on the model. Points with a Cook's Distance exceeding the threshold of $4/N$ (where N is the total number of observations) are considered influential and excluded. Refitting the model with the remaining data reduces the bias introduced by these extreme points.
- Blue Dashed Line (Robust Regression): Represents a model fitted using robust regression, which reduces the impact of outliers by assigning lower weights (via M-estimation) to data points with larger residuals, instead of removing them. This method ensures that the model retains all observations while minimizing the influence of extreme points.
- Green Dashed Line (Winsorization): Represents a model fitted using the Winsorization method, which caps extreme values at the 25th and 75th percentiles. Unlike Cook's Distance, this approach retains all observations, preventing overfitting by avoiding the exclusion of data. However, it may oversimplify the dataset by treating all extreme values as equal to the nearest threshold percentile.
- Yellow Line (Log-Transformed Model): Represents a model fitted using log transformation of the data. Log transformation linearizes relationships that are multiplicative or exponential, stabilizes variance, and reduces the impact of extreme values.

Note: The final model selected was a logarithmic regression with outliers removed using the Tukey method, which identifies and excludes extreme values based on interquartile range thresholds, yielding the best R^2 value.

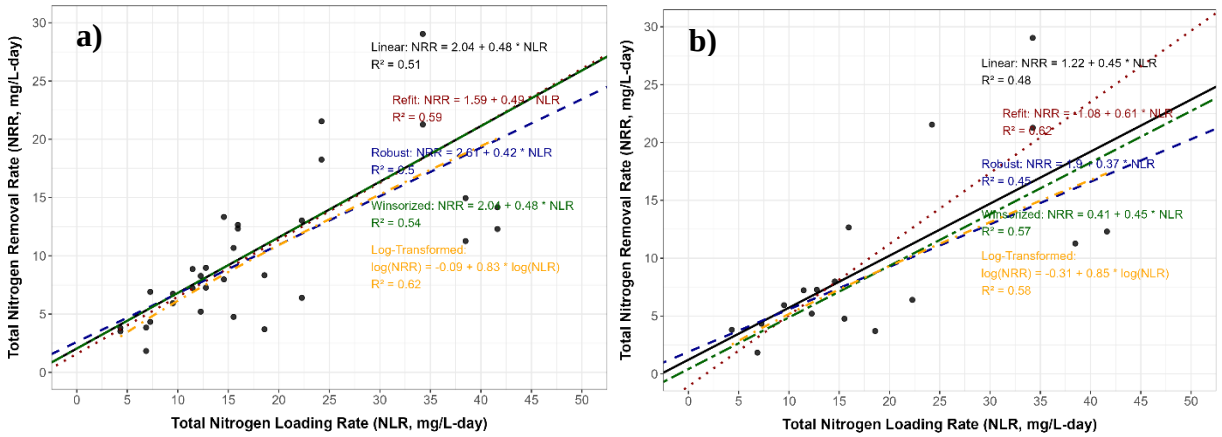


Figure S12. Linear regression with outlier removal methods for a) CBA unit and b) PBA unit.

An example of the R Script used to create the fitted model in Figure :

```
# --- 1. Standard Linear Regression ---
linear_model <- lm(NRR ~ NLR, data = data_clean_NLR_distinct)
linear_r2 <- summary(linear_model)$r.squared
linear_coeff <- coef(linear_model)

# --- 2. Cook's Distance ---
# Calculate Cook's distance
cooks_dist <- cooks.distance(linear_model)
threshold <- 4 / nrow(data_clean_NLR_distinct) # Common threshold
data_no_influential <- data_clean_NLR_distinct[cooks_dist < threshold, ]
refit_model <- lm(NRR ~ NLR, data = data_no_influential)
refit_r2 <- summary(refit_model)$r.squared
refit_coeff <- coef(refit_model)

# --- 3. Robust Regression ---
robust_model <- rlm(NRR ~ NLR, data = data_clean_NLR_distinct)
robust_coeff <- coef(robust_model)
# Calculate R^2 for robust regression
robust_pred <- predict(robust_model, data_clean_NLR_distinct)
robust_r2 <- 1 - sum((data_clean_NLR_distinct$NRR - robust_pred)^2) /
  sum((data_clean_NLR_distinct$NRR - mean(data_clean_NLR_distinct$NRR))^2)

# --- 4. Winsorization ---
data_winsorized <- data_clean_NLR_distinct %>%
  mutate(
    NLR = ifelse(NLR < quantile(NLR, 0.25), quantile(NLR, 0.25),
                 ifelse(NLR > quantile(NLR, 0.75), quantile(NLR, 0.75), NLR)),
    NRR = ifelse(NRR < quantile(NRR, 0.25), quantile(NRR, 0.25),
```

```
            ifelse(NRR > quantile(NRR, 0.75), quantile(NRR, 0.75), NRR))
  )
winsor_model <- lm(NRR ~ NLR, data = data_winsorized)
winsor_r2 <- summary(winsor_model)$r.squared
winsor_coeff <- coef(winsor_model)

# --- 5. Log Transformation ---
data_transformed <- data_clean_NLR_distinct %>%
  mutate(NLR_log = log(NLR), NRR_log = log(NRR))
log_model <- lm(NRR_log ~ NLR_log, data = data_transformed)
log_r2 <- summary(log_model)$r.squared
log_coeff <- coef(log_model)
```